CAPP

Center for
Axion and Precision
Physics Research

Proton EDM: High precision physics in storage rings for the best hadronic EDM experiment

Yannis K. Semertzidis, IBS/CAPP & KAIST

Turkish Physical Society 8th International Congress on Particle Accelerators and Applications (UPHUK VIII)

Online presentation, Bodrum, September 5, 2022

- At CAPP and before we have worked with several Turkish colleagues that have made all the difference! Physics is a supreme human activity knowing no boundaries/borders.
- The Center played a significant role in muon g-2 experiment and the srEDM collaboration finished the first comprehensive systematic error studies for the proton EDM experiment.

Prof. Cenap Ozben, ITU. A great scientist, colleague, mentor.

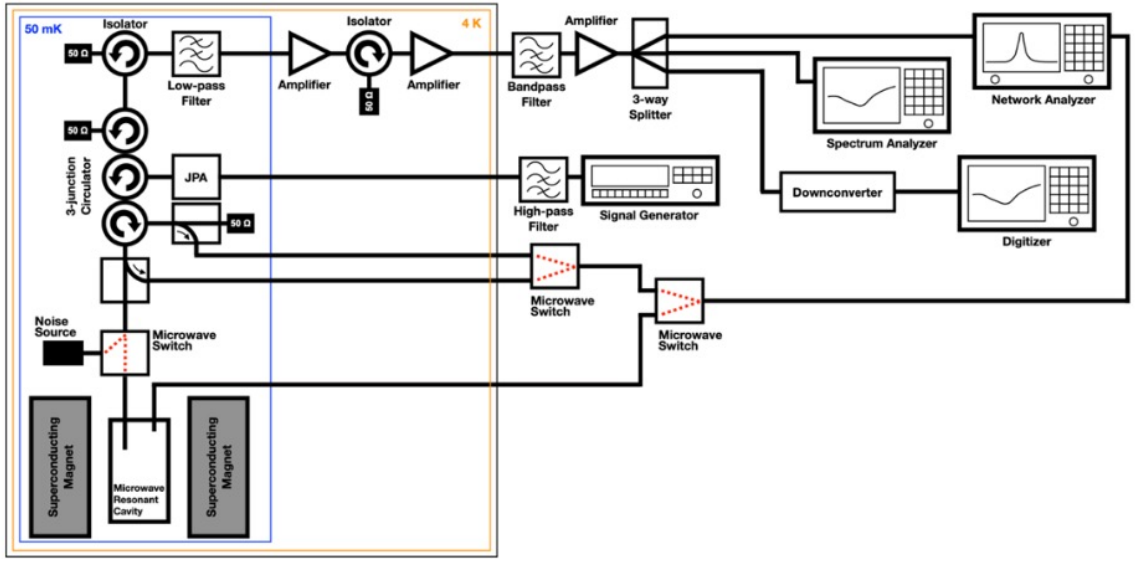
- CERN, 1994 worked together on SMC and “saved” the NMR calibration
- BNL, early 2000’s, worked on muon g-2, doing everything! CBO, pileup, resonances, fitting issues, etc.
- We are again collaborators on the srEDM experiment. Many of the issues are the same!!

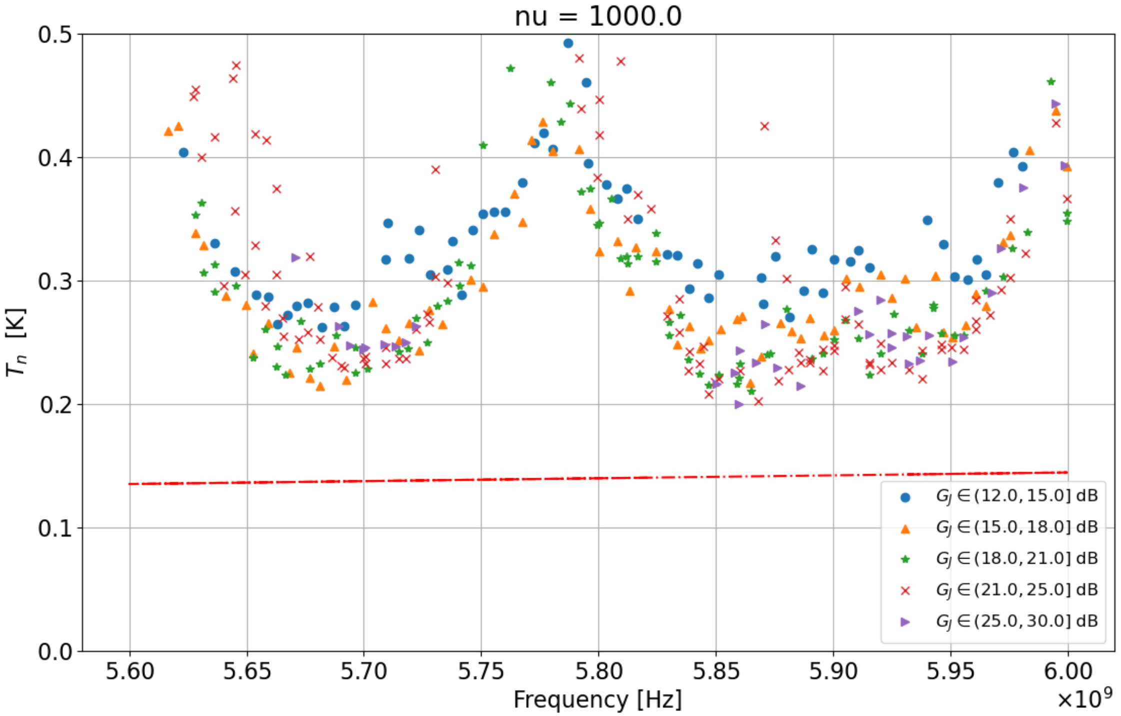
Beyoglu, Istanbul, August 6, 2022

Our 5.6-6 GHz JPA (Josephson Parametric Amplifiers)

Caglar Kutlu,
PhD student at KAIST

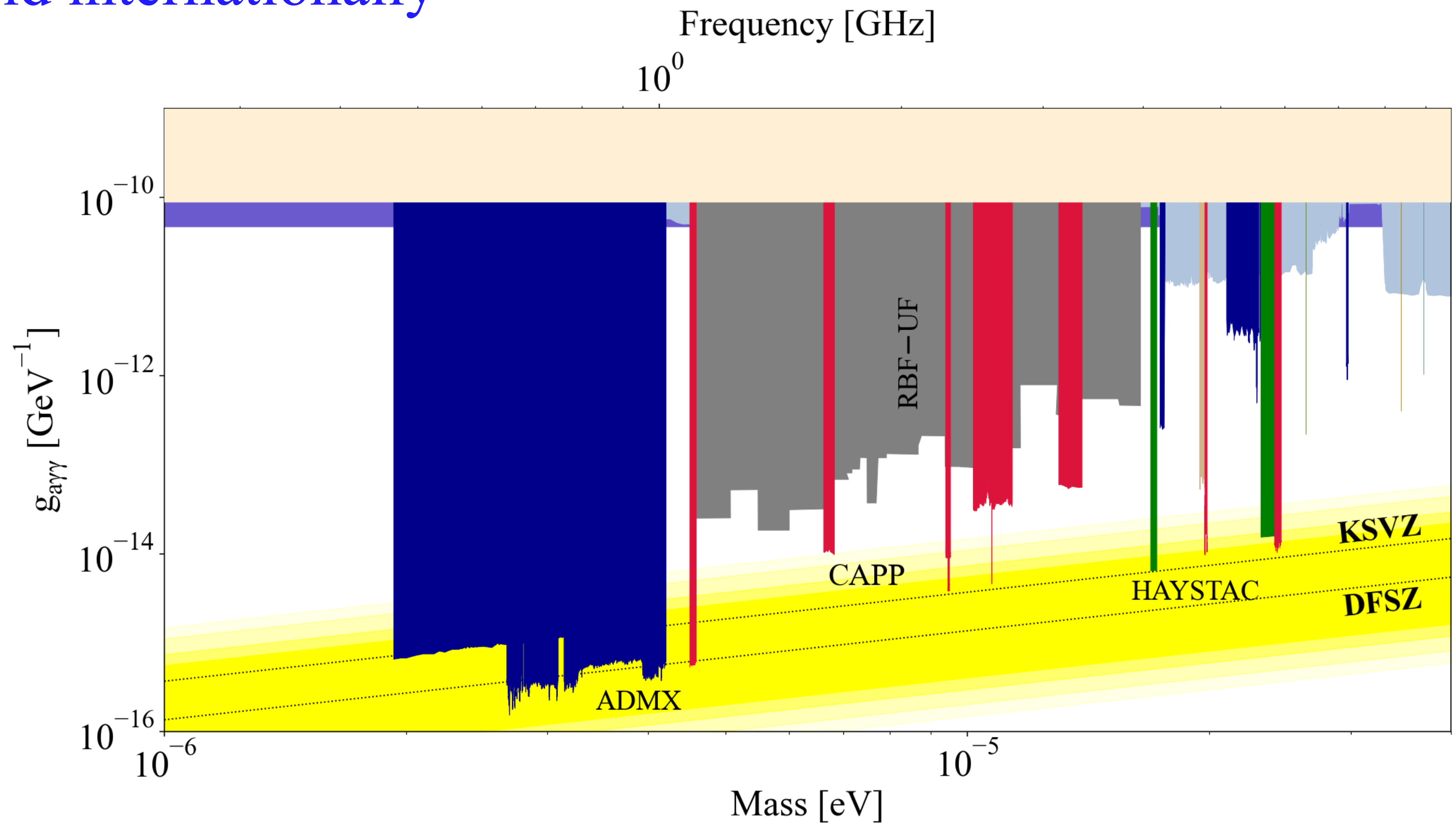
JPA installed in 8TB (BF6)
Noise temperature mapping





CAPP’s axion dark matter search is world-class (red)

- In large part due to Caglar Kutlu’s work on the JPAs (best systems in the world).
- Our recent DFSZ accomplishment is just the beginning, bringing us to the top of our field internationally



Accelerator based Precision physics research

- Muon g-2, good physics and training ground

- Storage ring electric dipole moment (srEDM) experiment development

Selcuk Haciomeroglu, CAPP.
Currently at Istinye
University, Istanbul

On Kim, PhD from
KAIST, Post doc

Zhanibek Omarov,
PhD from KAIST

Muon g-2 announcement, what does it mean?

- Physics: >8500 participants dialed in on “zoom” and Youtube channel during the announcement. It was estimated that the muon g-2 news reached >2.7B people.

- Blind analysis, meaning the frequency has a constant offset, so you don’t know the result when analyzing. The offset was set by Fermilab people outside the collaboration.

- The result is right on with the BNL value.

- The theory on hadronic contribution based on e^+e^- and lattice are at odds. The lattice work needs to be cross-checked and confirmed. Until then, we use e^+e^-.

Experiment and theory 4.2 sigma (theory based on e^+e^- data)

- Experiment:

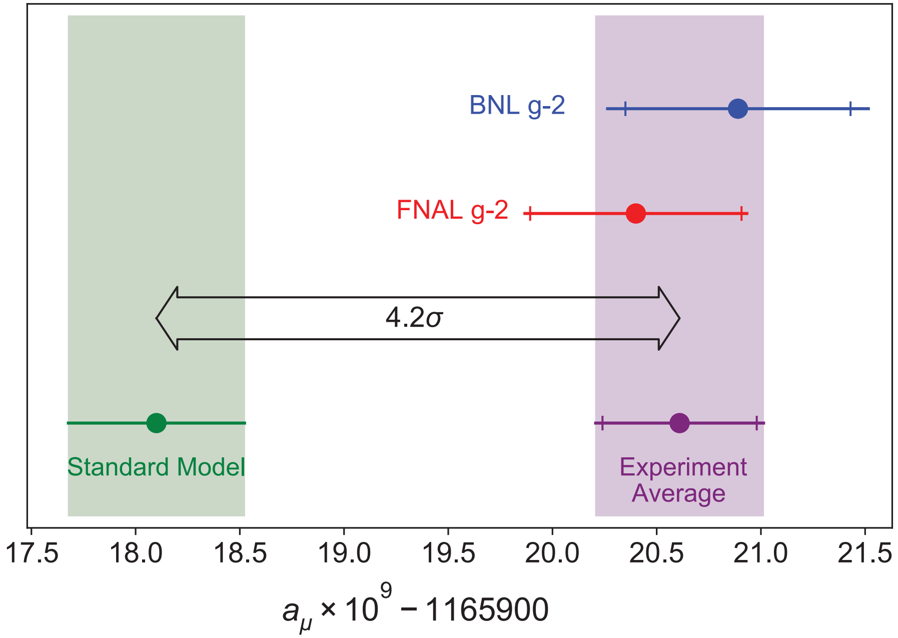
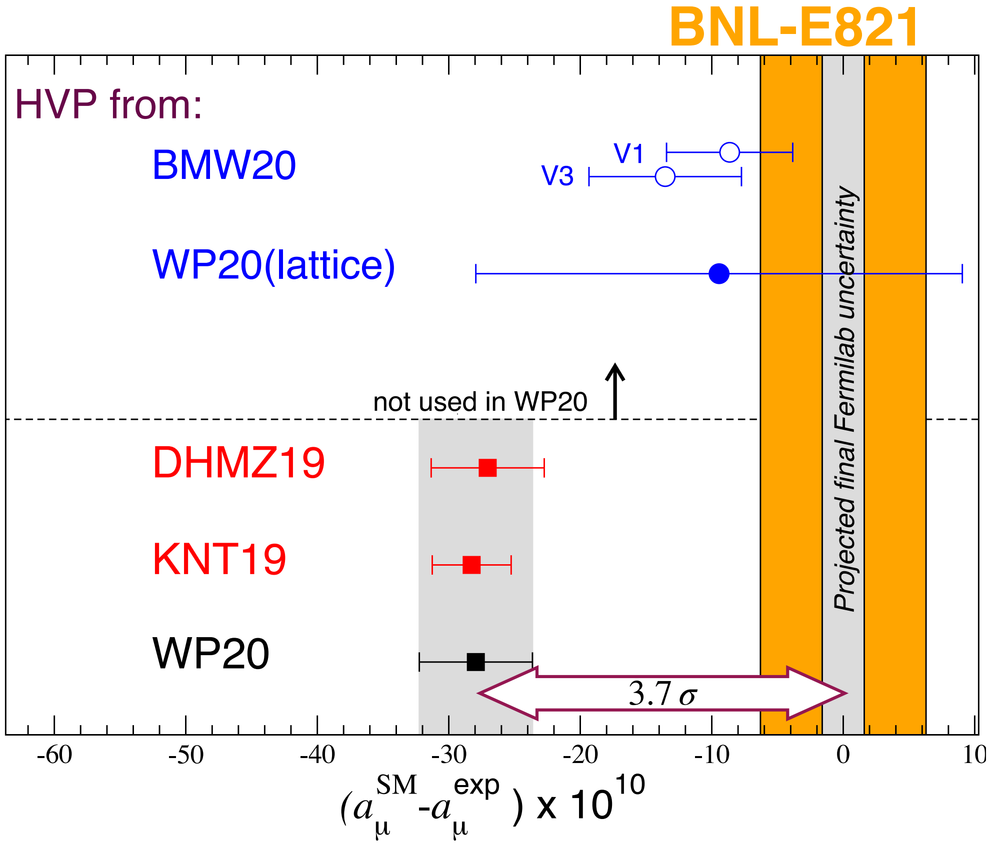


FIG. 4. From top to bottom: experimental values of a_μ from BNL E821, this measurement, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value [13] for the standard model is also shown.

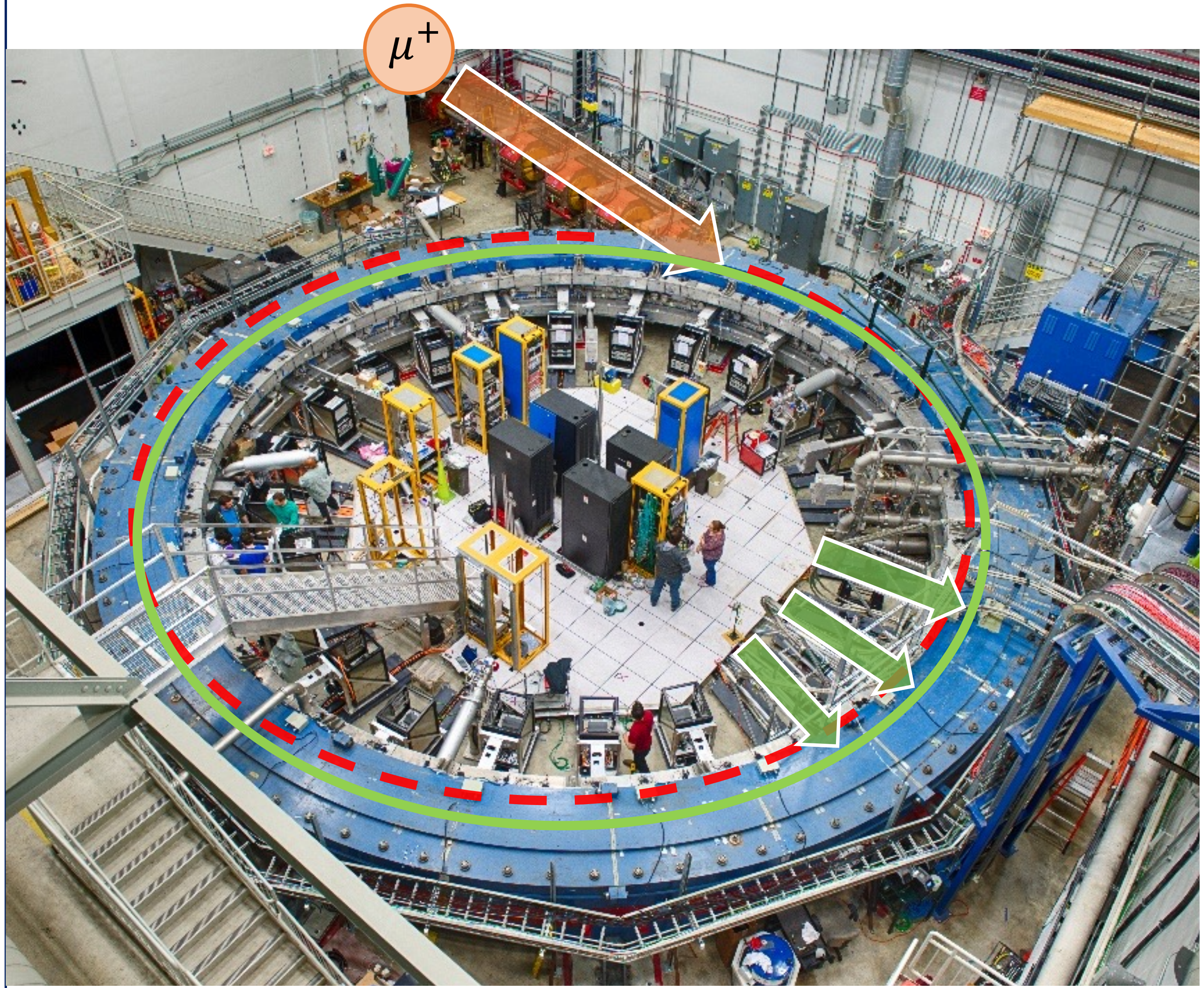
Theory status

- Theory:



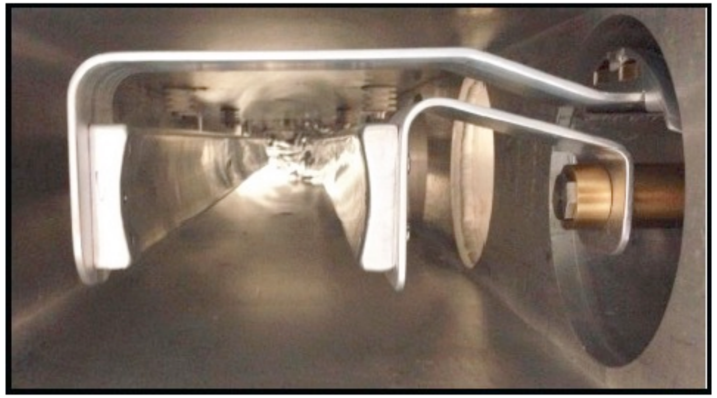
Theory based on lattice QCD (BMW collaboration) changed value significantly. Needs to be checked out first before considered seriously.

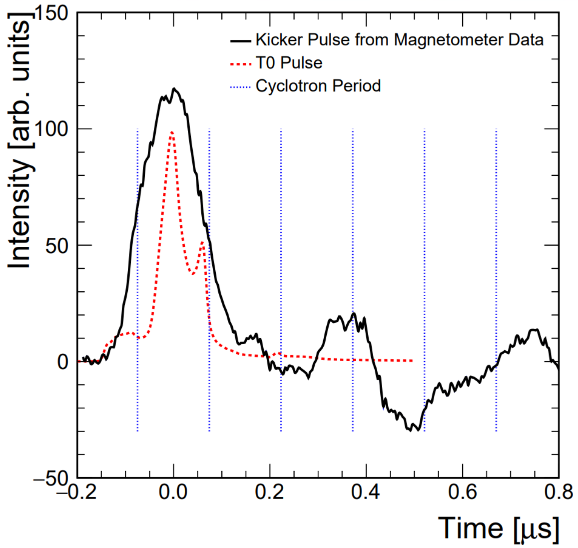
Overview of Muon $g-2$ Experiment at Fermilab (E989)



▶ Kick

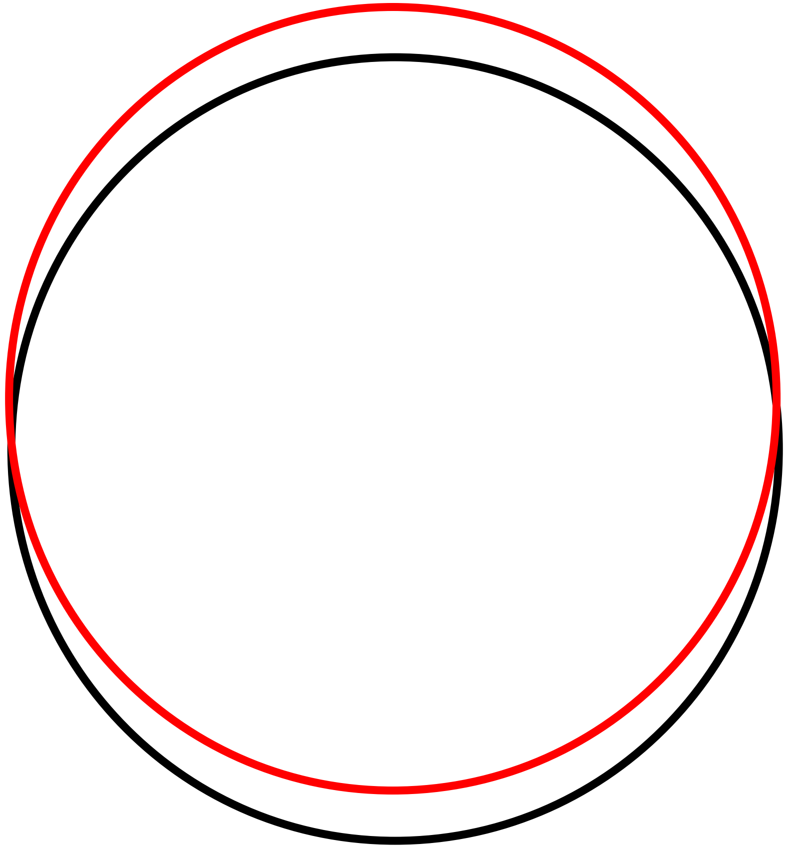
- Muons are kicked onto the design orbit by the fast non-ferric **kicker magnet** system.





Coherent betatron oscillations influence the g-2 phase

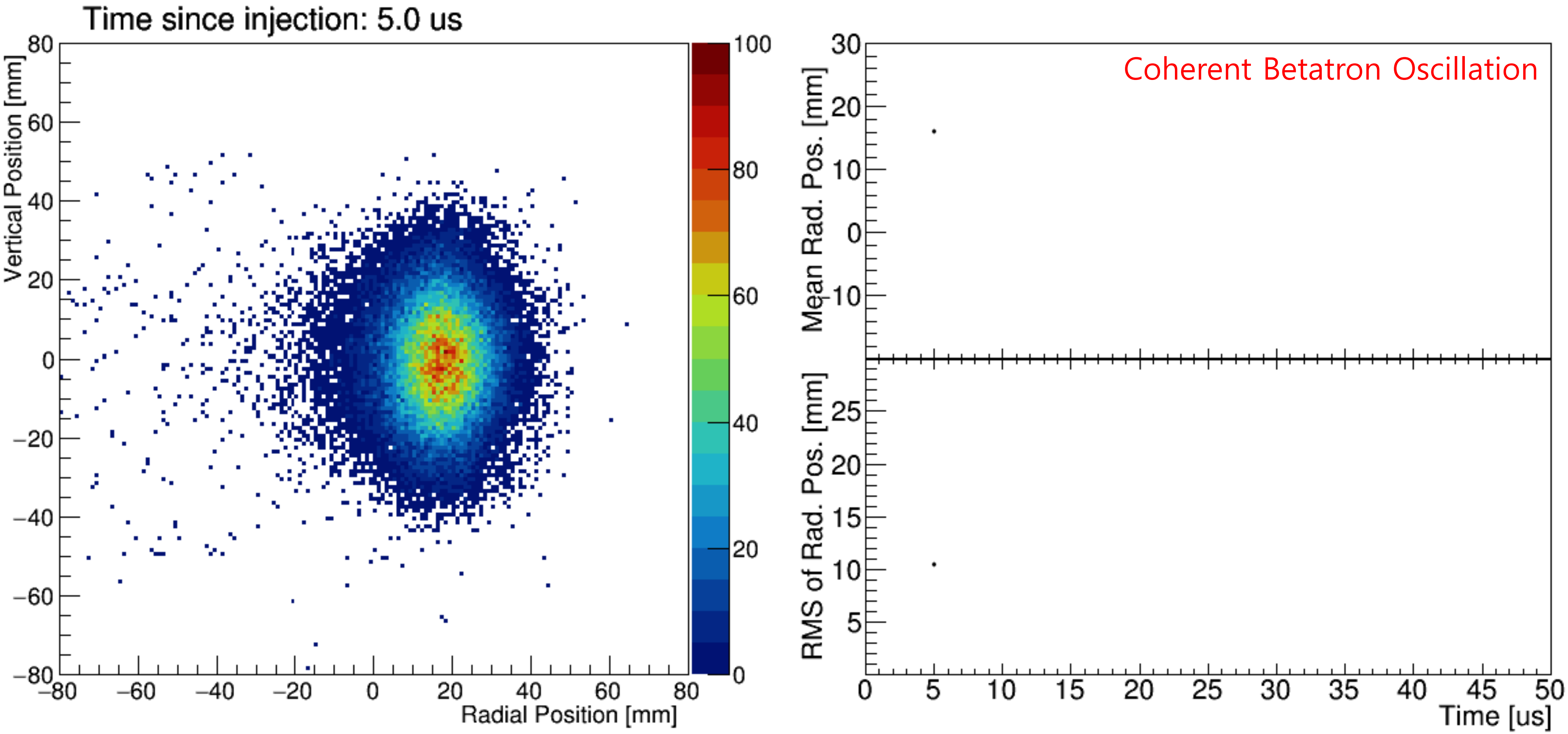
- CBO frequency $f_{cbo} = f_c\left(1-\sqrt{1-n}\right)$. Radial oscillations, through aliasing, became a problem
- A very high-frequency, cascaded through various effects down to g-2 frequency



Straw trackers

▶ Straw trackers

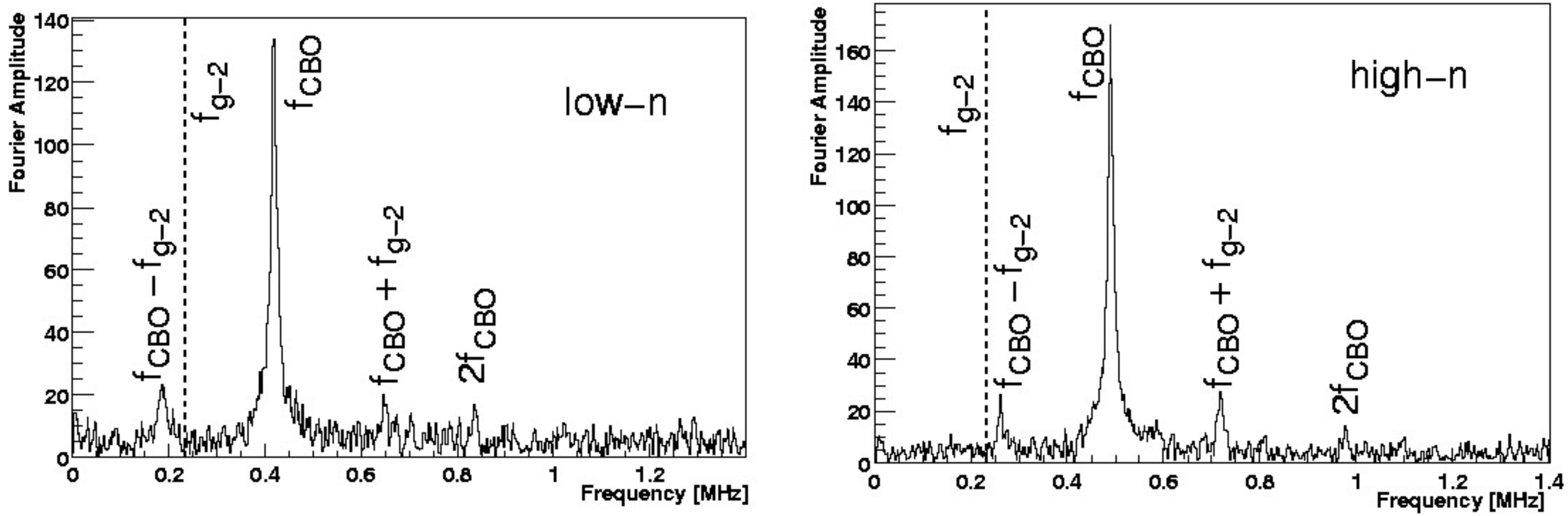
- Measures trajectories of the decay positrons and extrapolates to find the muon distribution.



CBO in the 2001 Data Set

$$f(t) = N_0 e^{-\lambda t}[1 + A\cos(\omega_a t + \phi)]$$

Residuals from fitting the 5-parameter function



CBO in the Data Set

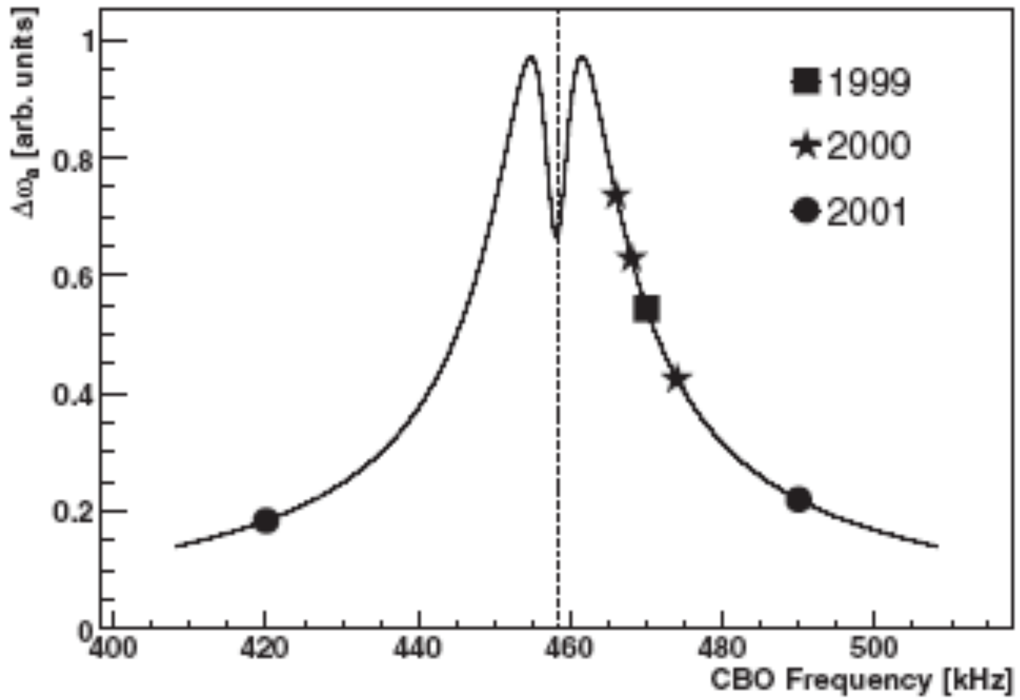
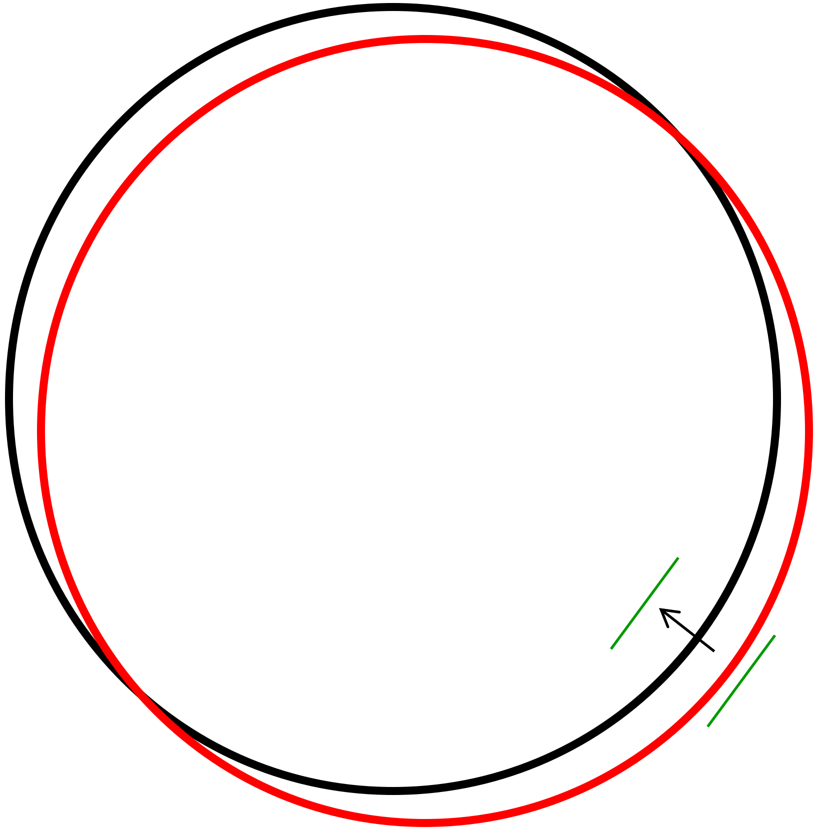


FIG. 36. The relative pull ($\Delta\omega$) versus the CBO modulation frequency *if not* addressed by the fitting function. A typical full vertical scale is several ppm; the actual scale depends on the specifics of the fit and the data set used. The R00 data were acquired under run conditions in which ω_a was very sensitive to CBO. This sensitivity was minimized in the R01 period where low- and high-n subperiods, each having CBO frequencies well below or above twice the $(g-2)$ frequency, were employed.

The effect depends on the CBO frequency

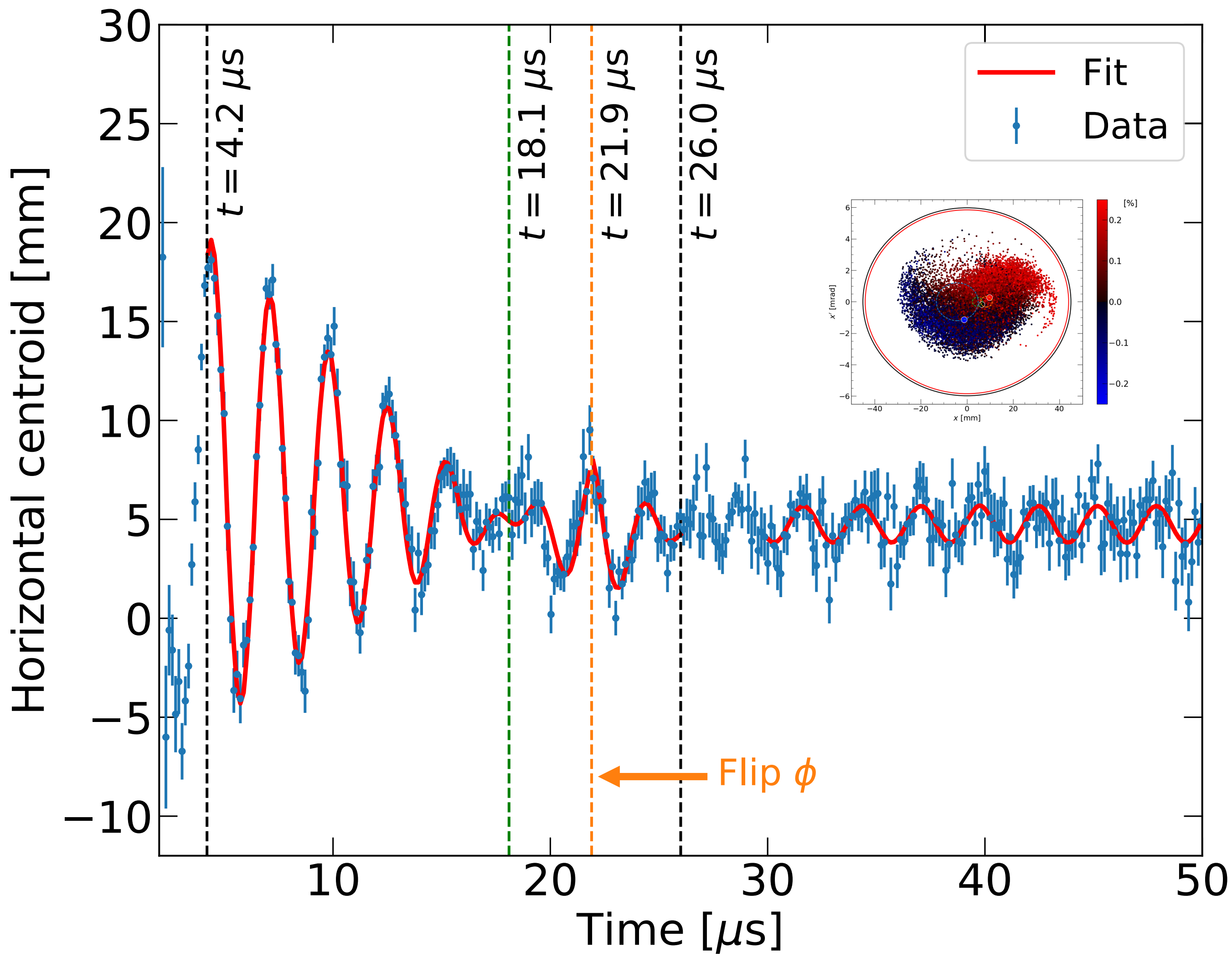
Prof. Cenap Ozben worked out the CBO physics for the muon g-2 Experiment at BNL

Yuri Orlov suggested to fix it by using a pair of plates (PE) as mini-kicker: We tried his method at Fermilab; it worked.



PE plates are 1m long
Apply rf E-field 470KHz

RF CBO amplitude reduction (data from muon g-2 experiment)



On Kim *et al*, New J. Phys. **22** (2020) 063002

Stroboscopic analysis method by Yuri Orlov

- When we realized the extent of the problem we had already taken the data. Actually, as it turns out, we were stuck with the CBO.

- What do you do with the data?

- Yuri Orlov: this is not a real resonance, but an observational one.

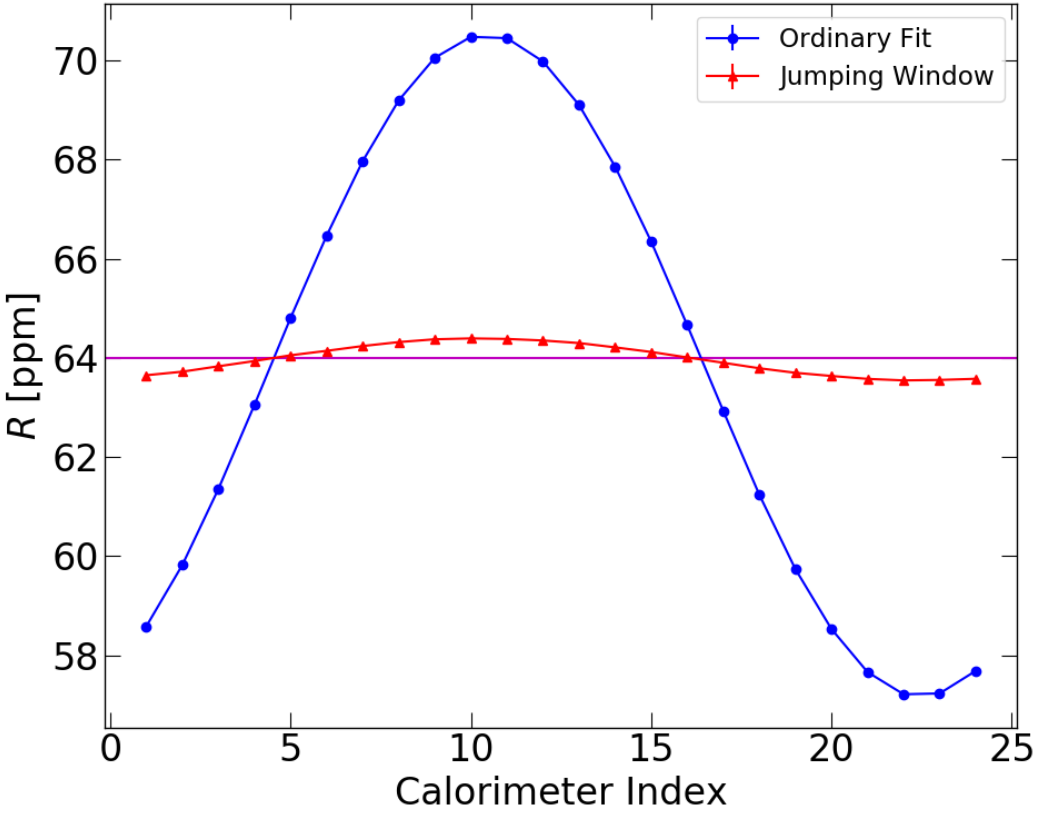
- Look at it at its own frequency… hence stroboscopic method, without needing to know the CBO functional form.

Stroboscopic method (a.k.a. Jumping Windows)

MC simulation (Constant f_{CBO})

- Ordinary fit vs. Stroboscopic fit (with five-parameter function)
  - Systematic biases are reduced by an order of magnitude!

- When our results are checked out using this method, we know our CBO models are correct

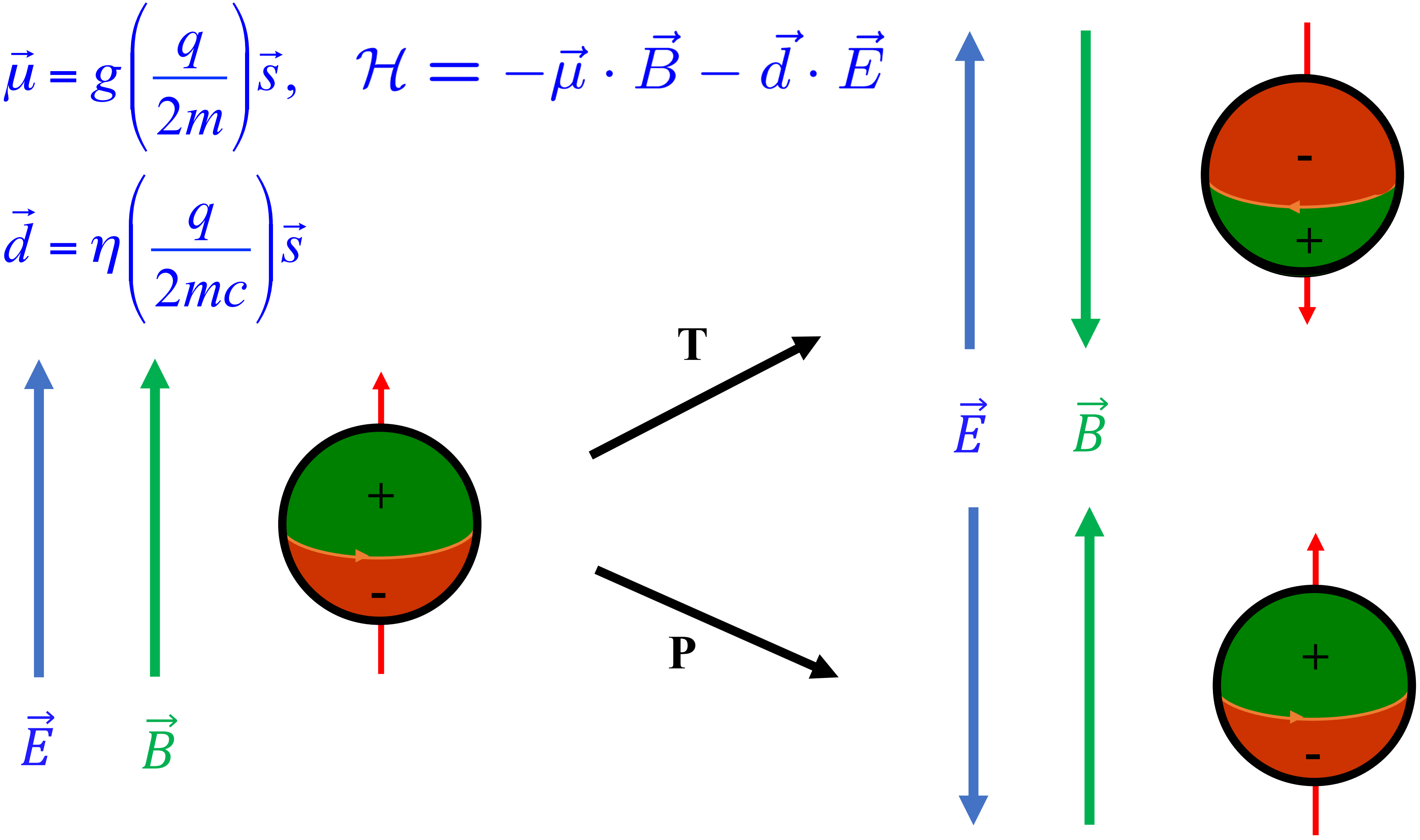


Electric Dipole Moments

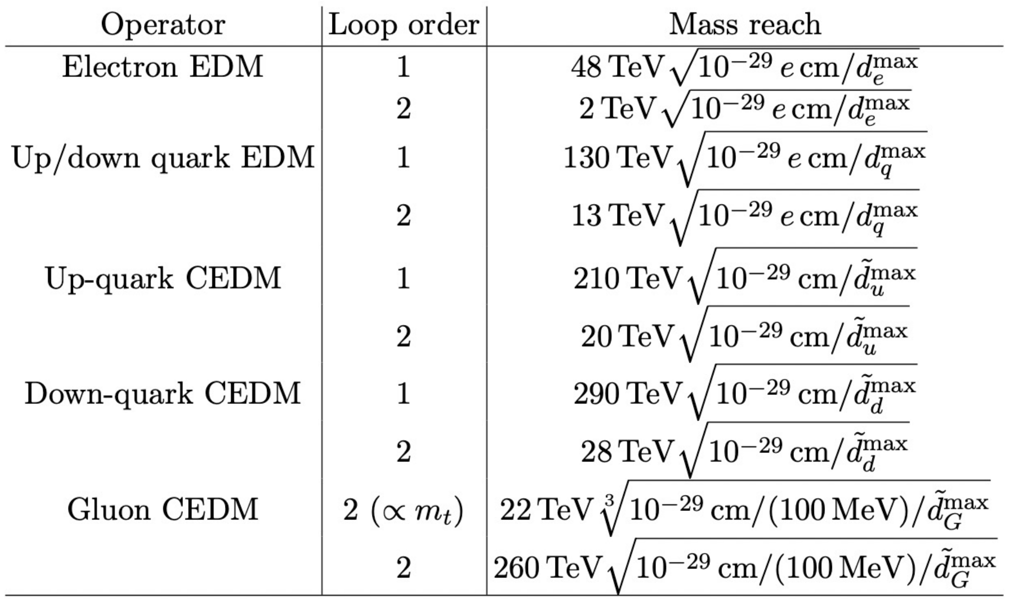
A Permanent EDM Violates both T & P Symmetries:

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}, \quad \mathcal{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

$$\vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

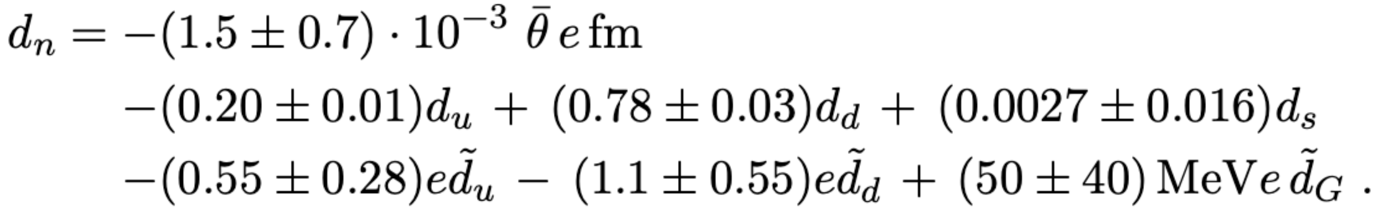


Snowmass paper on EDMs, why many EDMs:



Operator	Loop order	Mass reach
Electron EDM	1	$48\,\text{TeV}\sqrt{10^{-29}\,e\,\text{cm}/d_e^{\max}}$
	2	$2\,\text{TeV}\sqrt{10^{-29}\,e\,\text{cm}/d_e^{\max}}$
Up/down quark EDM	1	$130\,\text{TeV}\sqrt{10^{-29}\,e\,\text{cm}/d_q^{\max}}$
	2	$13\,\text{TeV}\sqrt{10^{-29}\,e\,\text{cm}/d_q^{\max}}$
Up-quark CEDM	1	$210\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/\tilde{d}_u^{\max}}$
	2	$20\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/\tilde{d}_u^{\max}}$
Down-quark CEDM	1	$290\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/\tilde{d}_d^{\max}}$
	2	$28\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/\tilde{d}_d^{\max}}$
Gluon CEDM	2 ($\propto m_t$)	$22\,\text{TeV}\sqrt[3]{10^{-29}\,\text{cm}/(100\,\text{MeV})/\tilde{d}_G^{\max}}$
	2	$260\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/(100\,\text{MeV})/\tilde{d}_G^{\max}}$

TABLE I. Crude estimate of the mass reach of different operators. See text for explanation of the notation and assumptions used in deriving the estimates.



$$
\begin{aligned}
d_n = &-(1.5 \pm 0.7) \cdot 10^{-3}\ \bar{\theta}\, e\,\text{fm} \\
&-(0.20 \pm 0.01) d_u + (0.78 \pm 0.03) d_d + (0.0027 \pm 0.016) d_s \\
&-(0.55 \pm 0.28) e\tilde{d}_u - (1.1 \pm 0.55) e\tilde{d}_d + (50 \pm 40)\,\text{MeV}\, e\,\tilde{d}_G\ .
\end{aligned}
$$

arXiv:2203.08103v1 [hep-ph] 15 Mar 2022

Electric dipole moments and the search for new physics

Ricardo Alarcon,[1] Jim Alexander,[2] Vassilis Anastassopoulos,[3] Takatoshi Aoki,[4] Rick Baartman,[5] Stefan Baeßler,[6,7] Larry Bartoszek,[8] Douglas H. Beck,[9] Franco Bedeschi,[10] Robert Berger,[11] Martin Berz,[12] Tanmoy Bhattacharya,[13,a] Michael Blaskiewicz,[14] Thomas Blum,[15,b] Themis Bowcock,[16] Kevin Brown,[14] Dmitry Budker,[17,18] Sergey Burdin,[16] Brendan C. Casey,[19] Gianluigi Casse,[20] Giovanni Cantatore,[21] Lan Cheng,[22] Timothy Chupp,[20] Vince Cianciolo,[23] Vincenzo Cirigliano,[13,24,c] Steven M. Clayton,[25] Chris Crawford,[26] B. P. Das,[27] Hooman Davoudiasl,[14] Jordy de Vries,[28,29,d] David DeMille,[30,31,e] Dmitri Denisov,[14] Milind V. Diwan,[14] John M. Doyle,[32] Jonathan Engel,[33] George Fanourakis,[34] Renee Fatemi,[35] Bradley W. Filippone,[36] Nadia Fomin,[37] Wolfram Fischer,[14] Antonios Gardikiotis,[38,3] R. F. Garcia Ruiz,[39] Claudio Gatti,[40] James Gooding,[16] Peter Graham,[41] Frederick Gray,[42] W. Clark Griffith,[43] Selcuk Haciomeroglu,[44] Gerald Gwinner,[45] Steven Hoekstra,[46,47] Georg H. Hoffstaetter,[2] Haixin Huang,[14] Nicholas R. Hutzler,[48,f] Marco Incagli,[10] Takeyasu M. Ito,[25,g] Taku Izubuchi,[49] Andrew M. Jayich,[50] Hoyong Jeong,[51] David Kaplan,[52] Marin Karuza,[53] David Kawall,[54] On Kim,[44] Ivan Koop,[55] Valeri Lebedev,[19] Jonathan Lee,[56] Soohyung Lee,[44] Kent K. H. Leung,[57] Chen-Yu Liu,[58,9,h] Joshua Long,[58,9] Alberto Lusiani,[59,10] William J. Marciano,[14] Marios Maroudas,[3] Andrei Matlashov,[44] Nobuyuki Matsumoto,[60] Richard Mawhorter,[61] Francois Meot,[14] Emanuele Mereghetti,[13] James P. Miller,[62] William M. Morse,[63,i] James Mott,[62,19] Zhanibek Omarov,[44,64] Chris O'Shaughnessy,[25] Cenap Ozben,[65] SeongTae Park,[44] Robert W. Pattie Jr.,[66] Alexander N. Petrov,[67,68] Giovanni Maria Piacentino,[69] Bradley R. Plaster,[26] Boris Podobedov,[14] Matthew Poelker,[70] Dinko Pocanic,[71] V. S. Prasannaa,[27] Joe Price,[16] Michael J. Ramsey-Musolf,[72,73] Deepak Raparia,[14] Surjeet Rajendran,[52] Matthew Reece,[74,j] Austin Reid,[58] Sergio Rescia,[14] Adam Ritz,[75] B. Lee Roberts,[62] Marianna S. Safronova,[76] Yasuhiro Sakemi,[77] Andrea Shindler,[78] Yannis K. Semertzidis,[44,64,k] Alexander Silenko,[79] Jaideep T. Singh,[80] Leonid V. Skripnikov,[67,68] Amarjit Soni,[14] Edward Stephenson,[58] Riad Suleiman,[81] Ayaki Sunaga,[82] Michael Syphers,[83] Sergey Syritsyn,[84] M. R. Tarbutt,[85] Pia Thoerngren,[86] Rob G. E. Timmermans,[87] Volodya Tishchenko,[14] Anatoly V. Titov,[67,68] Nikolaos Tsoupas,[14] Spyros Tzamarias,[88] Alessandro Variola,[40] Graziano Venanzoni,[10] Eva Vilella,[16] Joost Vossebeld,[16] Peter Winter,[89,l] Eunil Won,[51] Anatoli Zelenski,[14] Yan Zhou,[90] and Konstantin Zioutas[3]

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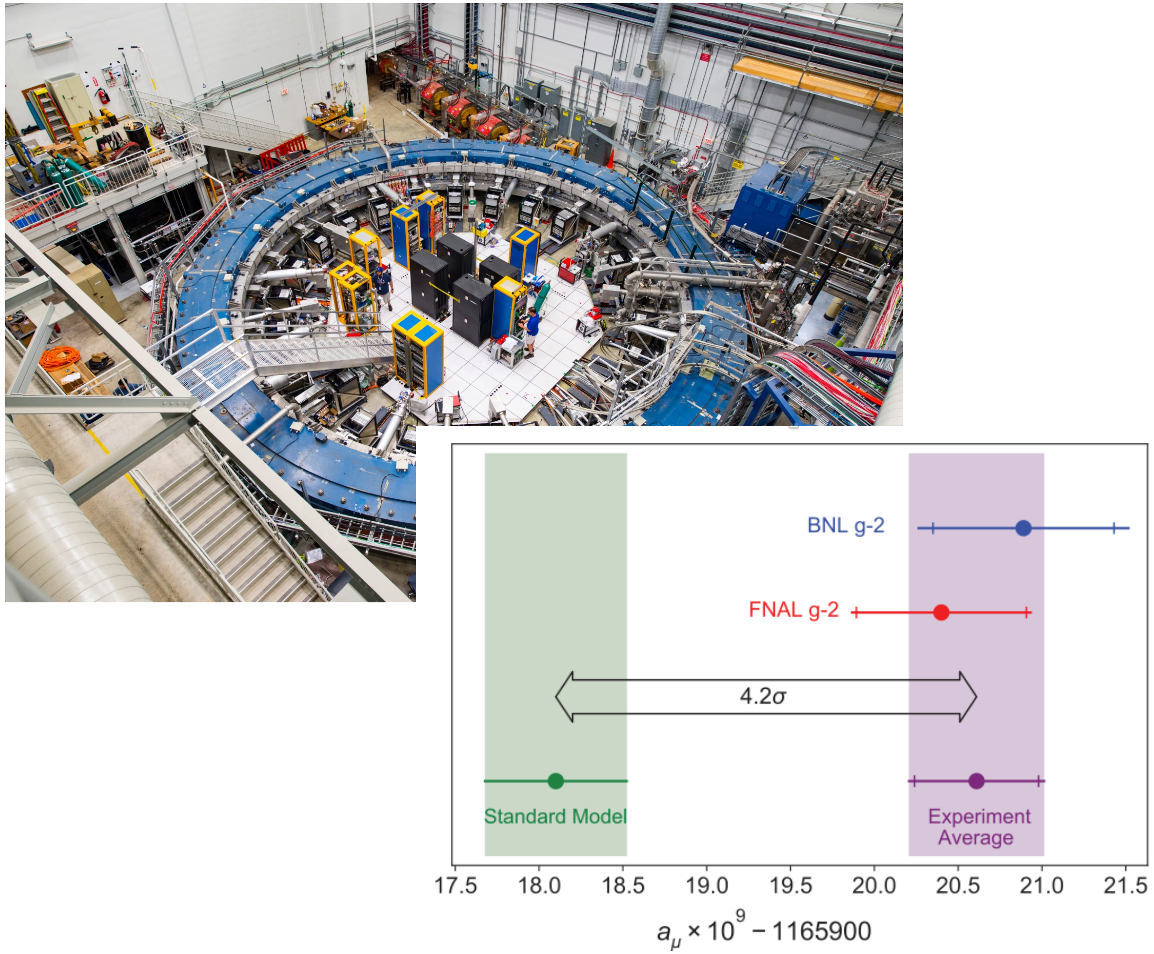
Snowmass paper on pEDM



Large fraction of the srEDM collaboration with muon g-2 experience

The storage ring proton EDM experiment

Jim Alexander[7], Vassilis Anastassopoulos[36], Rick Baartman[28], Stefan Baeßler[39,22], Franco Bedeschi[19], Martin Berz[17], Michael Blaskiewicz[4], Themis Bowcock[33], Kevin Brown[4], Dmitry Budker[9,31], Sergey Burdin[33], Brendan C. Casey[8], Gianluigi Casse[34], Giovanni Cantatore[38], Timothy Chupp[34], Hooman Davoudiasl[4], Dmitri Denisov[4], Milind V. Diwan[4], George Fanourakis[20], Antonios Gardikiotis[30,36], Claudio Gatti[18], James Gooding[33], Renee Fatemi[32], Wolfram Fischer[4], Peter Graham[26], Frederick Gray[23], Selcuk Haciomeroglu[6], Georg H. Hoffstaetter[7], Haixin Huang[4], Marco Incagli[19], Hoyong Jeong[16], David Kaplan[13], Marin Karuza[37], David Kawall[29], On Kim[6], Ivan Koop[5], Valeri Lebedev[14,8], Jonathan Lee[27], Soohyung Lee[6], Alberto Lusiani[25,19], William J. Marciano[4], Marios Maroudas[36], Andrei Matlashov[6], Francois Meot[4], James P. Miller[3], William M. Morse[4], James Mott[3,8], Zhanibek Omarov[15,6], Cenap Ozben[11], SeongTae Park[6], Giovanni Maria Piacentino[35], Boris Podobedov[4], Matthew Poelker[12], Dinko Pocanic[39], Joe Price[33], Deepak Raparia[4], Surjeet Rajendran[13], Sergio Rescia[4], B. Lee Roberts[3], Yannis K. Semertzidis [*6,15], Alexander Silenko[14], Amarjit Soni[4], Edward Stephenson[10], Riad Suleiman[12], Michael Syphers[21], Pia Thoerngren[24], Volodya Tishchenko[4], Nicholaos Tsoupas[4], Spyros Tzamarias[1], Alessandro Variola[18], Graziano Venanzoni[19], Eva Vilella[33], Joost Vossebeld[33], Peter Winter[2], Eunil Won[16], Anatoli Zelenski[4], and Konstantin Zioutas[36]

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arXiv:2205.00830v1 [hep-ph] 25 Apr 2022

Input to hadronic EDM

- Theta-QCD (part of the SM)

- CP-violation sources beyond the SM

A number of alternative simple systems could provide invaluable complementary information (e.g., proton, neutron and ^{3}He, deuteron,…).

- At 10^{-29}e•cm pEDM is at least an order of magnitude more sensitive than the current nEDM plans.

EDMs of different systems (Marciano)

Theta_QCD:

$$d_n \simeq -d_p \simeq 3\times 10^{-16}\,\overline{\theta}\ \mathrm{e\cdot cm}$$

$$d_D\left(\overline{\theta}\right)/d_N\left(\overline{\theta}\right) \approx 1/3$$

Super-Symmetry (SUSY) model predictions:

$$d_n \simeq 1.4\left(d_d - 0.25 d_u\right) + 0.83e\left(d_u^c + d_d^c\right) - 0.27e\left(d_u^c - d_d^c\right)$$

$$d_p \simeq 1.4\left(d_d - 0.25 d_u\right) + 0.83e\left(d_u^c + d_d^c\right) + 0.27e\left(d_u^c - d_d^c\right)$$

$$d_D \simeq \left(d_u + d_d\right) - 0.2e\left(d_u^c + d_d^c\right) - 6e\left(d_u^c - d_d^c\right)$$

$$d_N^{I=1} \simeq 0.87\left(d_u - d_d\right) + 0.27e\left(d_u^c - d_d^c\right)$$

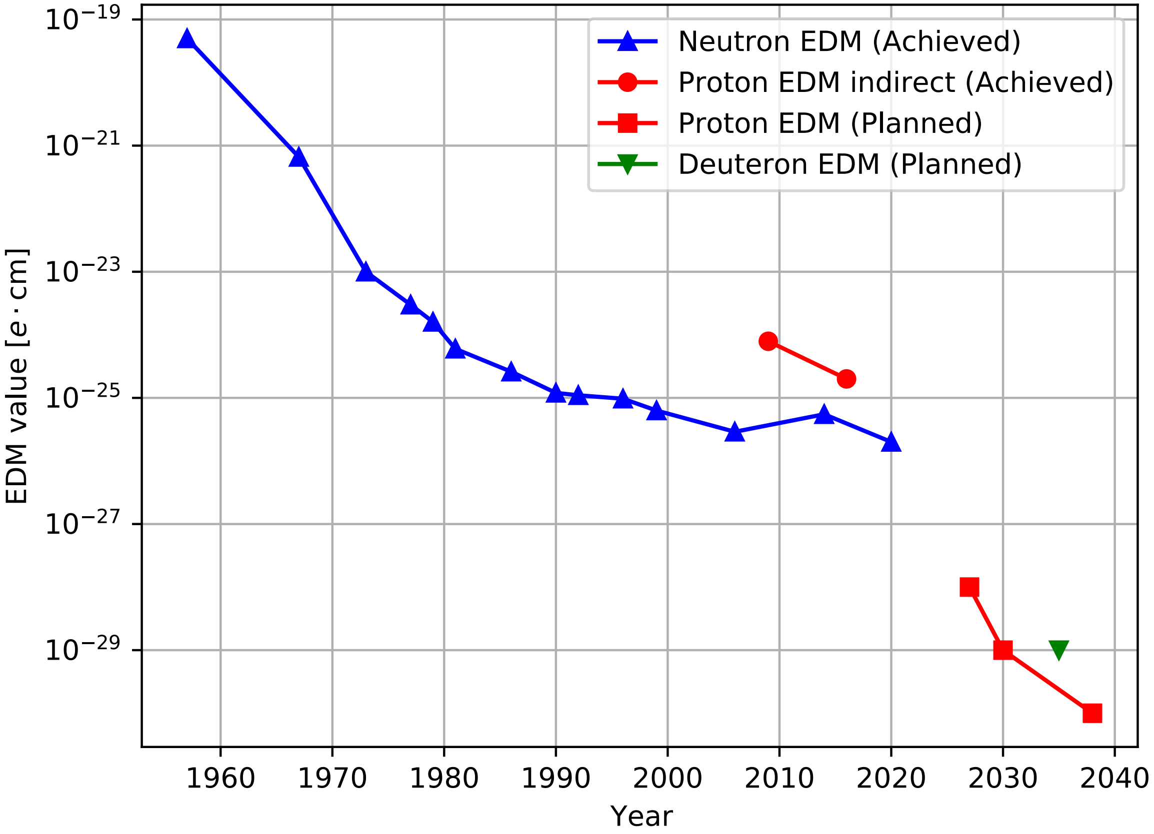
$$d_N^{I=0} \simeq 0.5\left(d_u + d_d\right) + 0.83e\left(d_u^c + d_d^c\right)$$

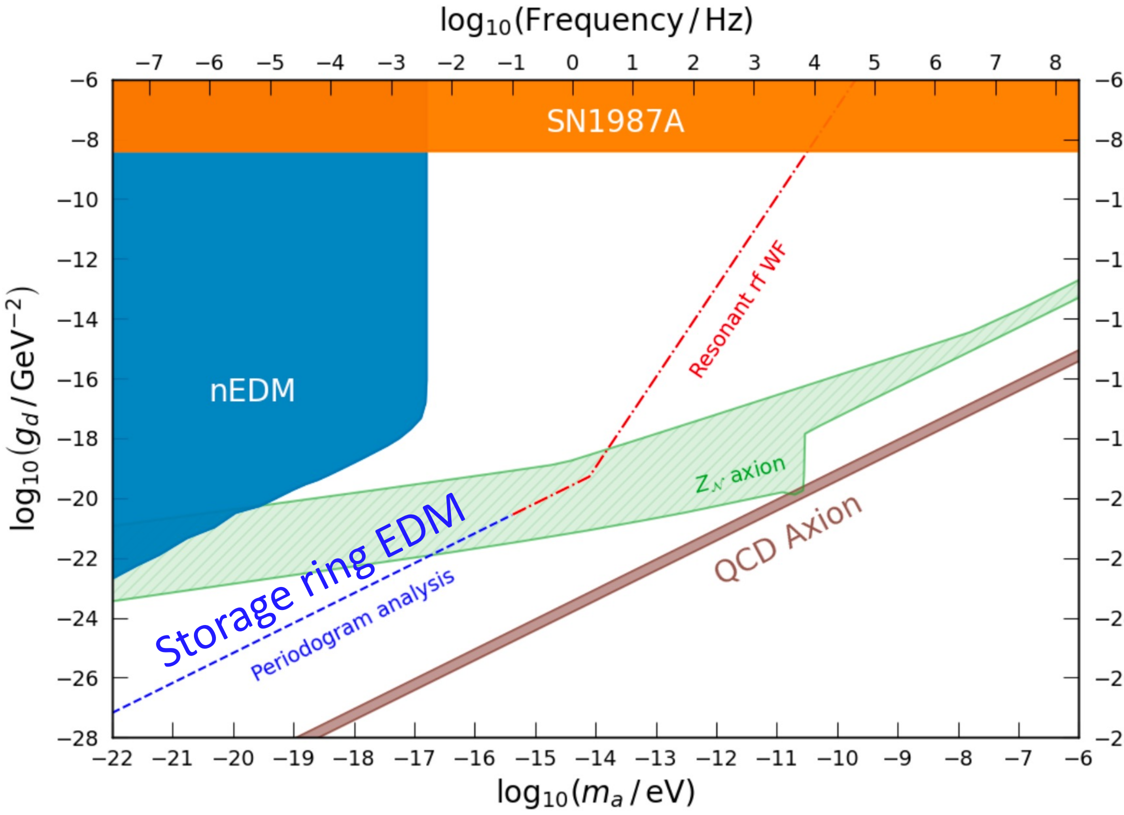
$$d_N^{I=1} = \left(d_p - d_n\right)/2$$

$$d_N^{I=0} = \left(d_p + d_n\right)/2$$

Storage ring proton EDM at 10^{-29} *e*-cm: Timeline, physics reach

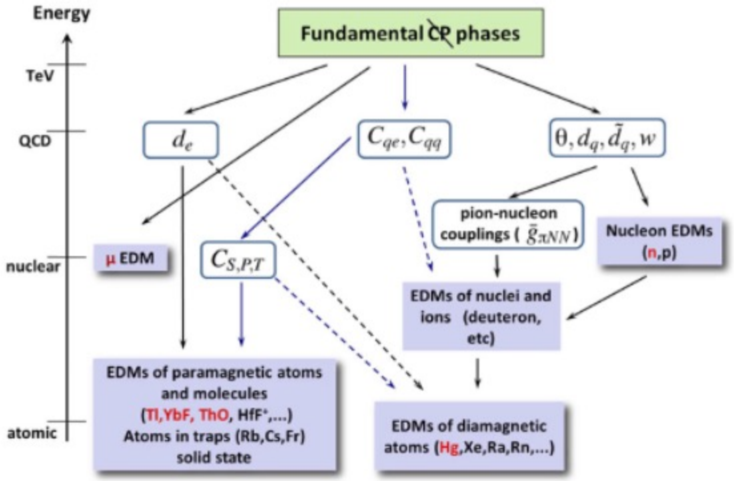
- In progress or still ahead: Snowmass, CDR, proposal/TDR, ring construction, injection, storage.
- Experience with muon g-2 experiment; possible to have interesting results within the decade.
- Competitive EDM sensitivity:
  - New-Physics reach at 10^3 TeV.
  - Best probe on Higgs CPV, Marciano: proton is better than H→ $\gamma\gamma$, and 30x more sensitive than electron with same EDM.
  - Three orders of magnitude improvement in θ_{QCD} sensitivity.
  - Direct axion dark matter reach (best exp. sensitivity at very low frequencies).

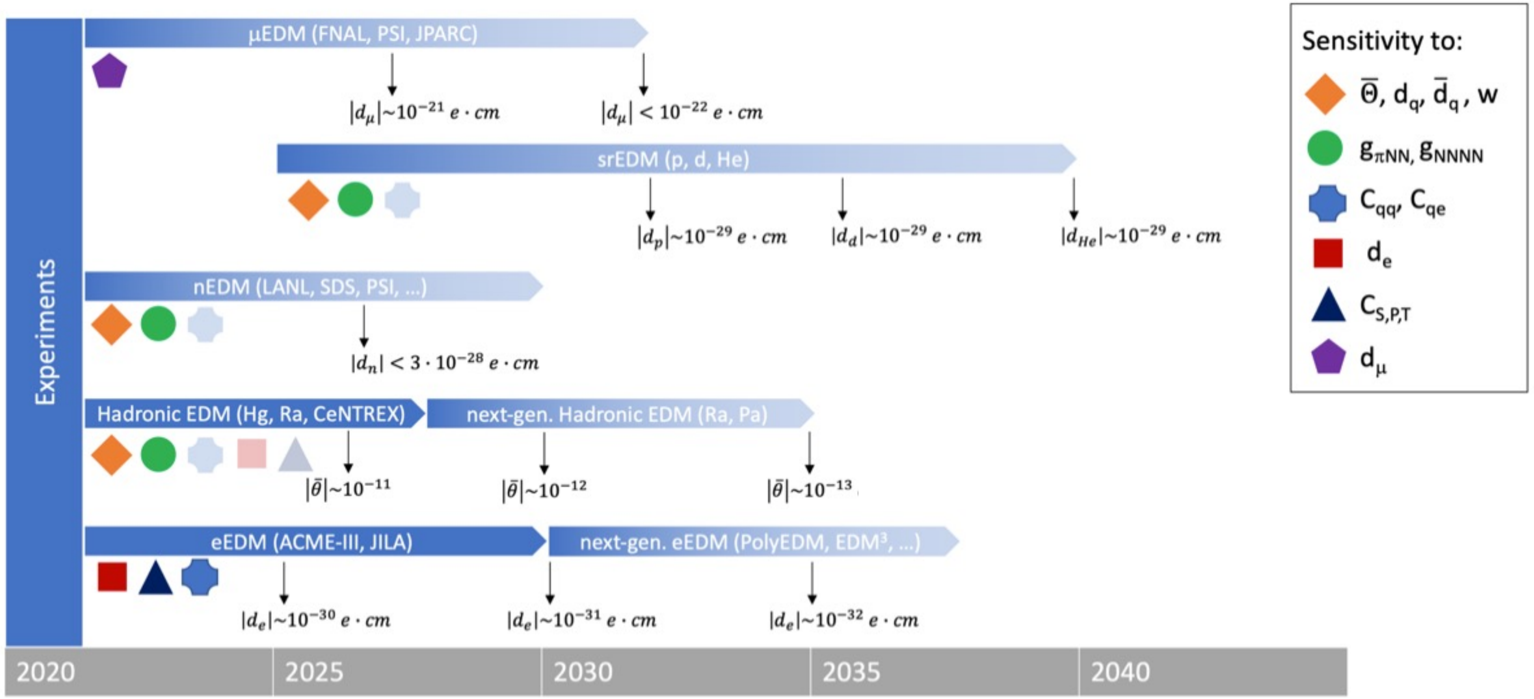




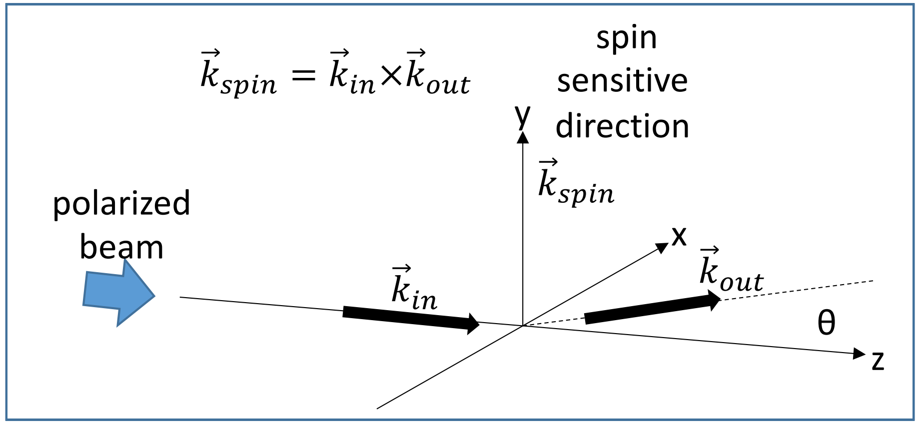
Electric Dipole Moments

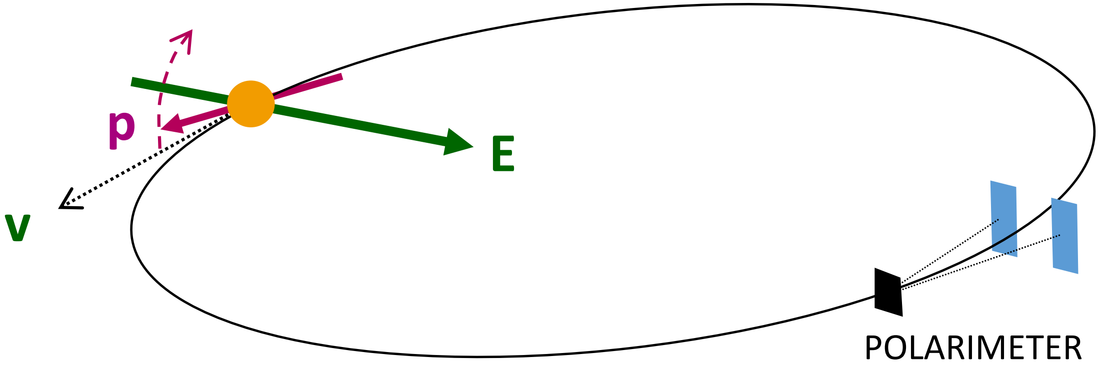
They set the current limits on SUSY-like New-Physics





Storage ring Electric Dipole Moments





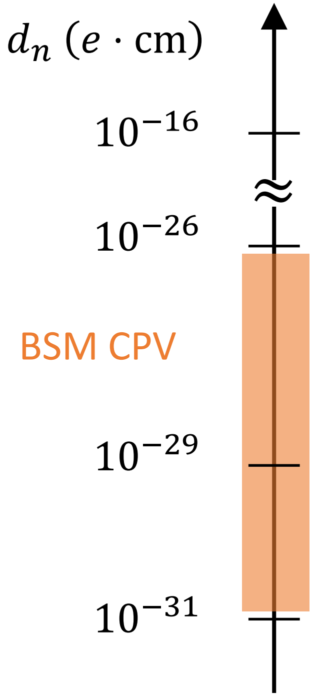
Frozen spin method:

- Spin aligned with the momentum vector
- Radial E-field precesses EDM/spin vertically
- Monitoring the spin using a polarimeter

On Kim’s slide from his Snowmass talk

Physics motivation

- Big question: Is there BSM CPV?



“Natural” order from Strong CPV $\bar{\theta} \approx \mathcal{O}(1)$

Experimental upper limit ⇒ Strong CP problem: $\bar{\theta} \lesssim 10^{-10}$

Physics reach of $d_p \approx \mathcal{O}(10^{-29})$ $e \cdot \mathrm{cm}$:

1. Three orders of magnitude improvement in $\bar{\theta}$.
2. Sensitive to $M_{\mathrm{NP}} \approx \mathcal{O}(10^{1-3})$ TeV.
3. Baryogenesis ($\approx 10^{-28}$ $e \cdot \mathrm{cm}$ expected in MSSM).
4. Two-loop Higgs coupling: $\tan \phi_{\mathrm{NP}} \approx \mathcal{O}(10^{-4})$.

Projected pEDM sensitivity.

Upper bound from the SM expectation (Weak CPV: CKM & PMNS)

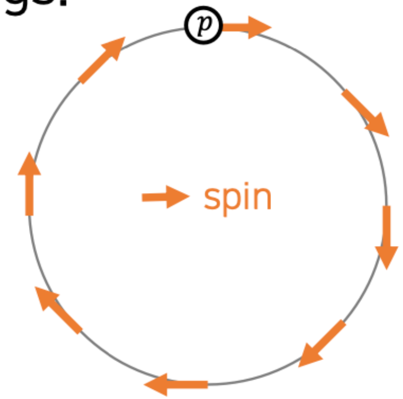
- Storage ring pEDM experiment
  - First “direct” measurement/constraint of d_p with improvement by 10^3 from the best current d_n limit.
  - Complementary to atomic & molecular EDM experiments.
  - Dedicated ALP/vector dark matter or dark energy search.

Storage ring pEDM in a nutshell

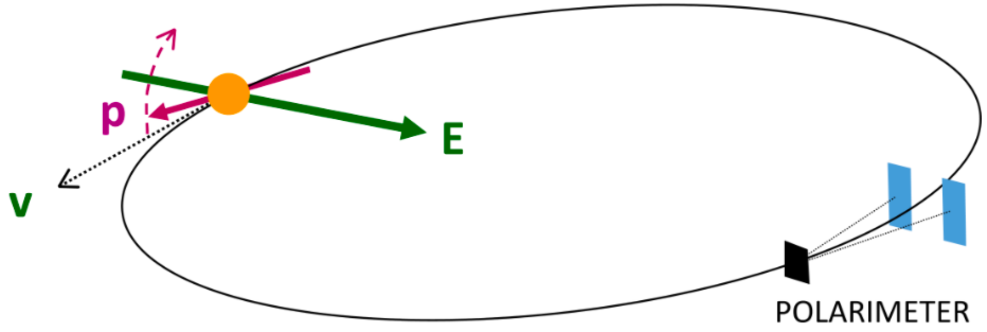
On Kim’s slide from his Snowmass talk

- Frozen-spin method: The most sensitive setup for probing the EDM in storage rings.
  - Spin is “frozen” with respect to the momentum.
  - Spin slowly precesses in vertical direction due to radial $\mathbf{E}$.

$$\frac{\mathbf{ds}}{\mathrm{d}t} = \mathbf{d} \times \mathbf{E}$$



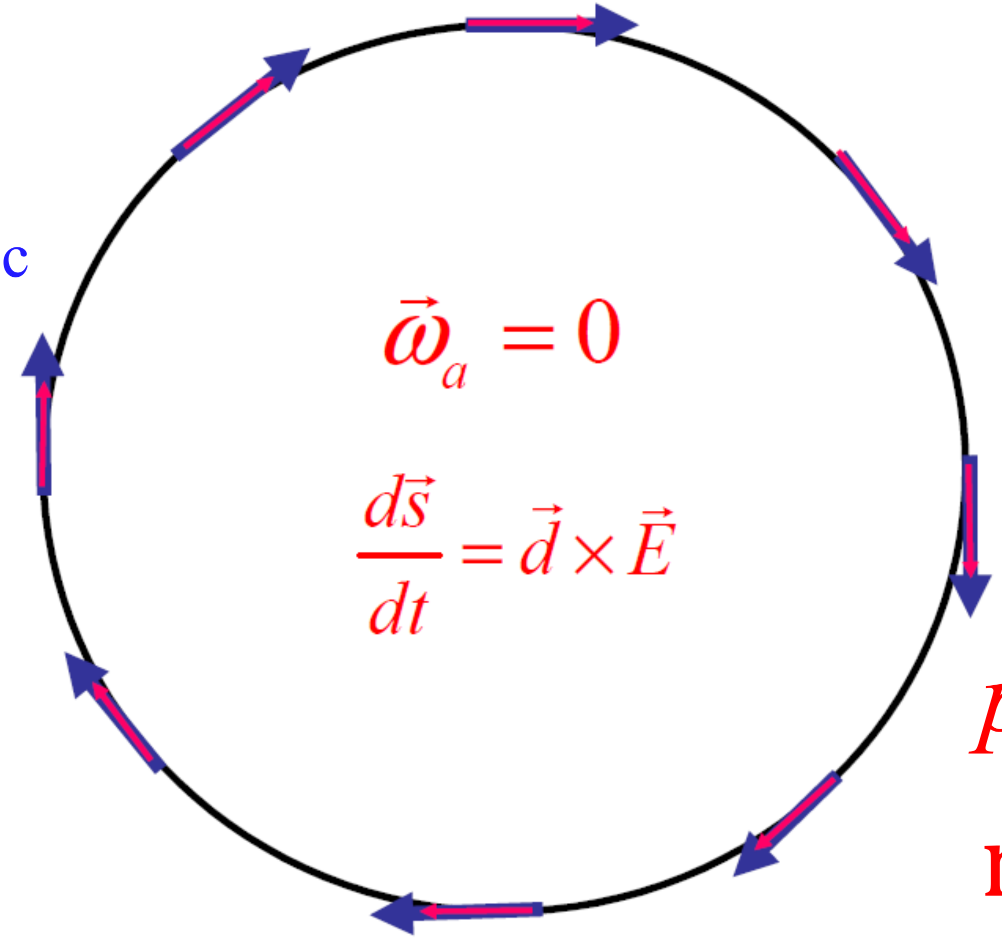
- Protons should be at “magic” momentum $\approx 0.7\ \mathrm{GeV/c}$.
- Vertical polarization is measured by left-right asymmetry from the polarimeter.
  - $d_p = 10^{-29}\ e \cdot \mathrm{cm}$ corresponds to $1\ \mathrm{nrad/s}$ precession rate in the vertical polarization.
  - Takes one year of data accumulation with realistic parameters.
- It is an extremely high-intensity measurement.
  Understanding/controlling systematic uncertainties is everything.
  - Field errors, beam distribution, geometrical phases, closed-orbit planarity, ⋯.



Storage Ring EDM experiments, frozen spin method

Pure electric bending, w/ “magic” momentum

F.J.M. Farley *et al.*, “A new method of measuring electric dipole moments in storage rings,” Phys. Rev. Lett. 93, 052001 (2004)



$$\vec{\omega}_a = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

$p = \frac{mc}{\sqrt{a}}$, a: magnetic moment anomaly

Electric fields: Freezing the g-2 spin precession

$$\vec{\omega}_a = -\frac{q}{m}\left[a - \left(\frac{mc}{p}\right)^2\right]\frac{\vec{\beta}\times\vec{E}}{c} = 0$$

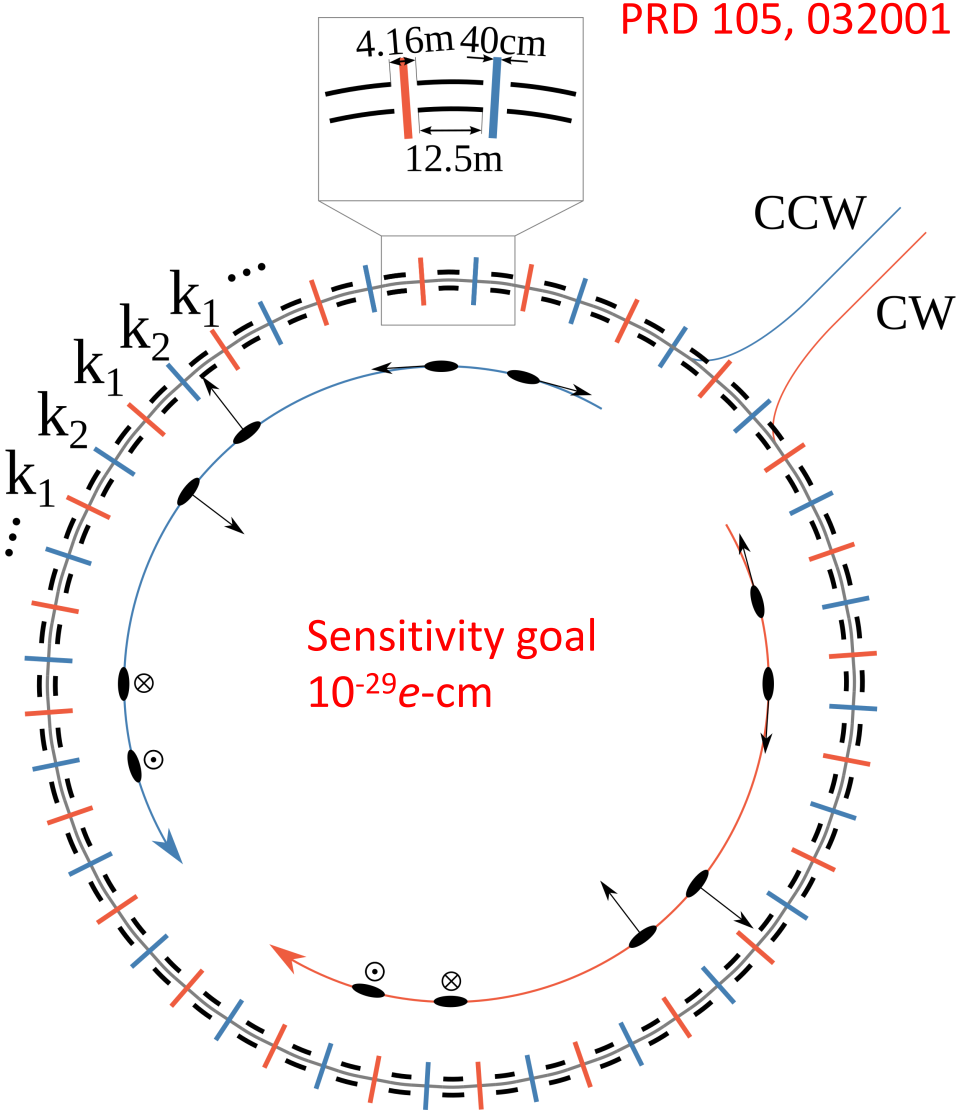
- The g-2 spin precession is zero at “magic” momentum (3.1GeV/c for muons,…), so the focusing system can be electric

$$p = \frac{mc}{\sqrt{a}}, with\ a = G = \frac{g-2}{2}, \gamma_m = \sqrt{1+1/a}$$

- The “magic” momentum concept with electric focusing was first used in the last muon g-2 experiment at CERN, at BNL & FNAL.

Hybrid, symmetric lattice storage ring
Lattice parameters by Val Lebedev

PRD 105, 032001 (2022)



Sensitivity goal

10^{-29}*e*-cm

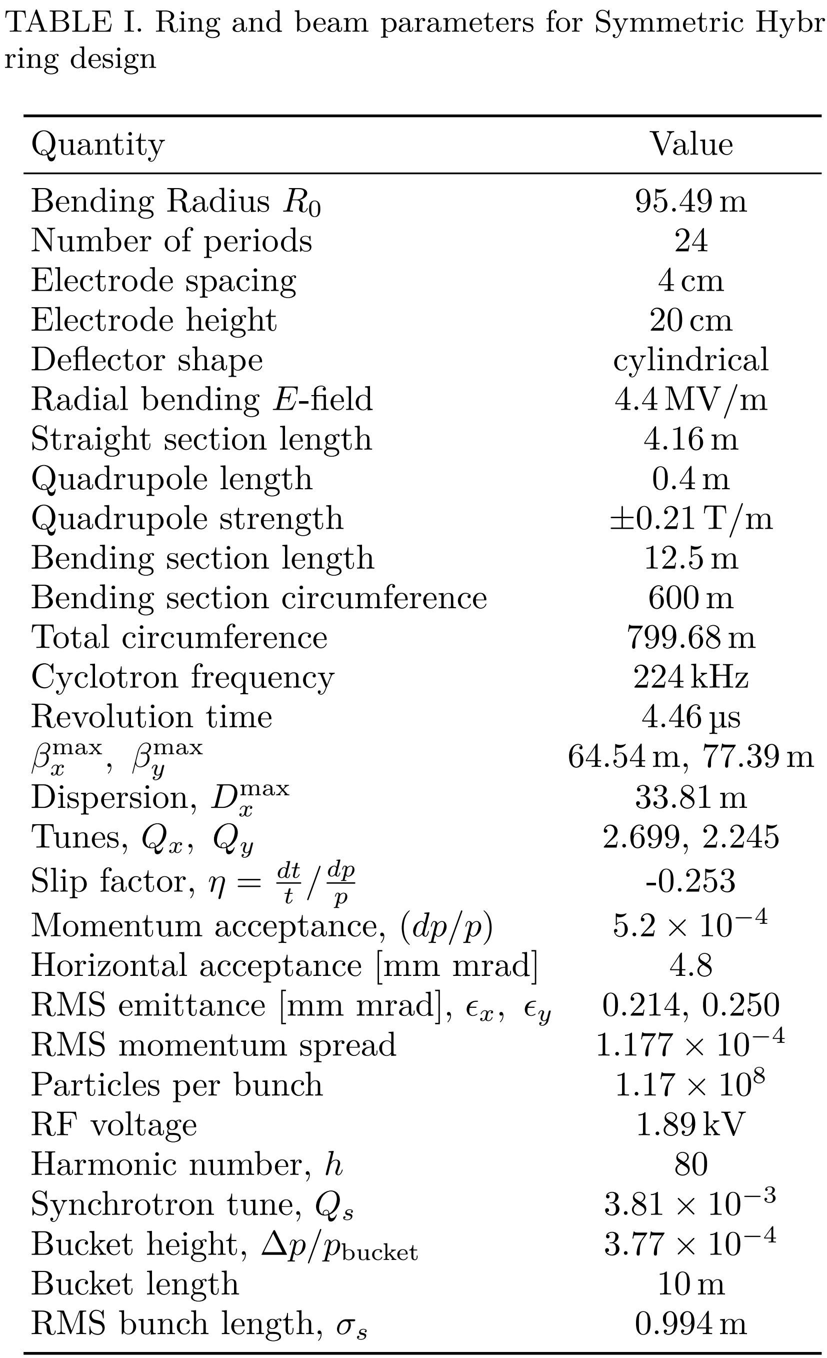


TABLE I. Ring and beam parameters for Symmetric Hybrid ring design

Quantity	Value
Bending Radius R_0	95.49 m
Number of periods	24
Electrode spacing	4 cm
Electrode height	20 cm
Deflector shape	cylindrical
Radial bending E-field	4.4 MV/m
Straight section length	4.16 m
Quadrupole length	0.4 m
Quadrupole strength	±0.21 T/m
Bending section length	12.5 m
Bending section circumference	600 m
Total circumference	799.68 m
Cyclotron frequency	224 kHz
Revolution time	4.46 µs
$\beta_x^{\max}$, $\beta_y^{\max}$	64.54 m, 77.39 m
Dispersion, $D_x^{\max}$	33.81 m
Tunes, Q_x, Q_y	2.699, 2.245
Slip factor, $\eta = \frac{dt}{t} / \frac{dp}{p}$	-0.253
Momentum acceptance, (dp/p)	5.2×10^{-4}
Horizontal acceptance [mm mrad]	4.8
RMS emittance [mm mrad], ϵ_x, ϵ_y	0.214, 0.250
RMS momentum spread	1.177×10^{-4}
Particles per bunch	1.17×10^{8}
RF voltage	1.89 kV
Harmonic number, h	80
Synchrotron tune, Q_s	3.81×10^{-3}
Bucket height, $\Delta p/p_{\text{bucket}}$	3.77×10^{-4}
Bucket length	10 m
RMS bunch length, σ_s	0.994 m

Low risk

Strong focusing

Proton Statistical Error (232MeV): 10^{-29} *e*-cm

Phys. Rev. D **104**, 096006 (2021)

$$\boxed{\sigma_d = \frac{2.33\hbar}{E_R P A \sqrt{N_c f \tau_p T_{tot}}}}$$

τ_p : 2×10^{3}s Polarization Lifetime (Spin Coherence Time)
A : 0.6 Left/right asymmetry observed by the polarimeter
P : 0.8 Beam polarization
N_c : 4×10^{10}p/cycle Total number of stored particles per cycle (10^{3}s)
T_{Tot}: 2×10^{7}s Total running time per year
f : 1% Useful event rate fraction (efficiency for EDM)
E_R : 4.5 MV/m Radial electric field strength

Systematic errors

^{3}He Co-magnetometer in nEDM experiment

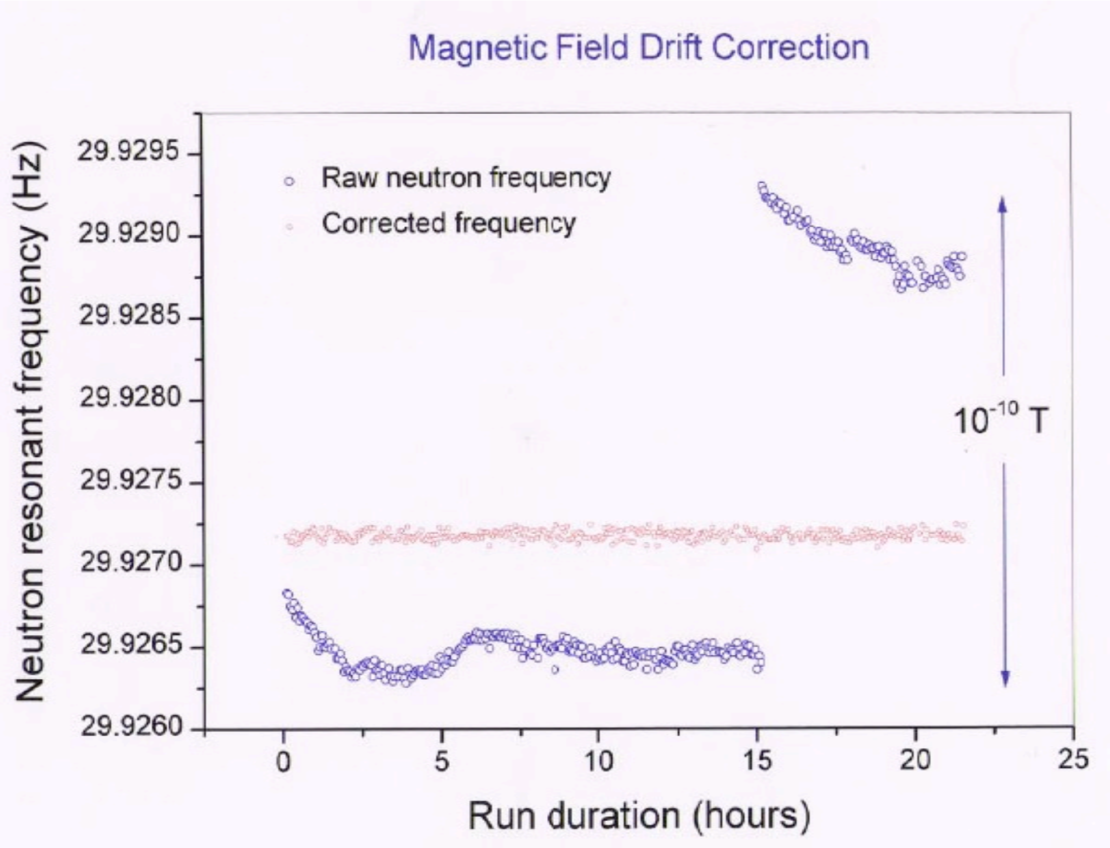
If nEDM = 10^{-26} e·cm,

10 kV/cm → 0.1 μHz shift

≅ B field of 2×10^{-15} T.

Co-magnetometer :

Uniformly samples the B Field faster than the relaxation time.



Data: ILL nEDM experiment with ^{199}Hg co-magnetometer

EDM of ^{199}Hg < 10^{-28} e-cm (measured); atomic EDM ~ Z^2 → ^{3}He EDM << 10^{-30} e-cm

Under gravity, the center of mass of He-3 is higher than UCN by Δh ≈ 0.13 cm, sets ΔB = 30 pGauss (1 nA of leakage current). $\Delta B/B = 10^{-3}$.

Storage Ring Electric Dipole Moments exp. options

Fields	Example	EDM signal term	Comments
Dipole magnetic field **(B)** **(Parasitic)**	Muon g-2	Tilt of the spin precession plane. **(Limited statistical sensitivity due to spin precession)**	Eventually limited by geometrical alignment. **Requires consecutive CW and CCW injection to eliminate systematic errors**
Combination of electric & and magnetic fields **(E, B)** **(Combined lattice)**	Deuteron, ^{3}He, proton, muon, etc.	Mainly: $\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B}\right)}$	High statistical sensitivity. **Requires consecutive CW and CCW injection with main fields flipping sign to eliminate systematic errors**
Radial Electric field **(E)** & Electric focusing **(E)** **(All electric lattice)**	Proton, etc.	$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$	Large ring, CW & CCW storage. **Requires demonstration of adequate sensitivity to radial B-field syst. error**
Radial Electric field **(E)** & Magnetic focusing **(B)** **(Hybrid, symmetric lattice)**	Proton, etc.	$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$	Large ring, CW & CCW storage. **Only lattice to achieve direct cancellation of main systematic error sources (its own "co-magnetometer").** GOLD STANDARD!

Effect as a function of azimuthal harmonic N

COMPREHENSIVE SYMMETRIC-HYBRID RING DESIGN FOR A … PHYS. REV. D **105,** 032001 (2022)

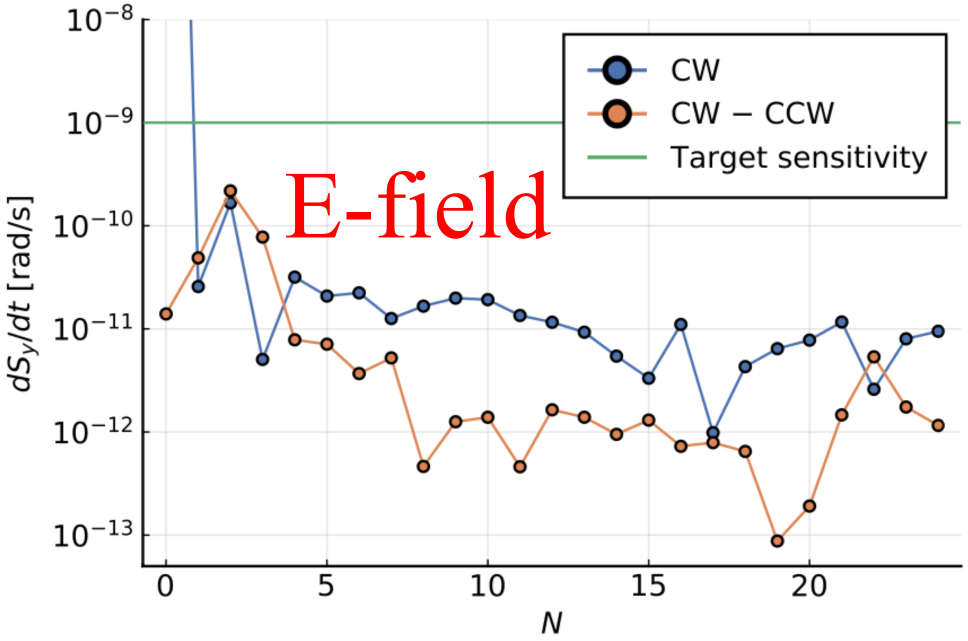


FIG. 7. *Longitudinal polarization case* $S_s = 1$, sensitive to EDM. Vertical spin precession rate vs $E_y = 10$ V/m field N harmonic around the ring azimuth. For $N = 0$, the precession rate for the CW (or CCW) beam is around 5 rad/s. The difference of the precession rates for CR beams (orange) is below the target sensitivity for all N. Irregularities of the low values are due to the inability to determine the exact precession rate from the simulation results. Hence, the points only show a statistical upper limit of the possible vertical precession rate; actual rates could be lower. More about this is in Appendix B.

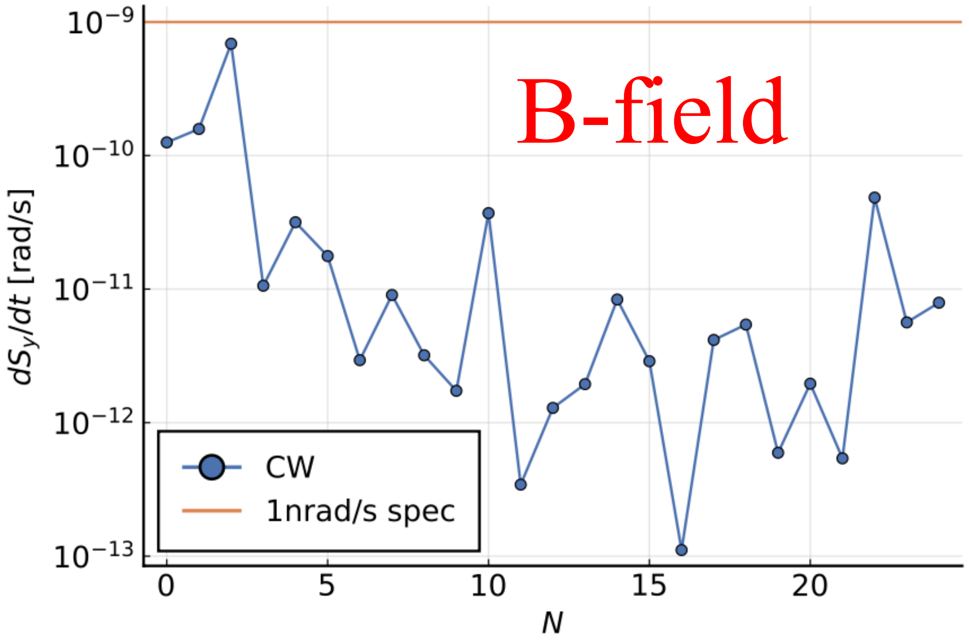
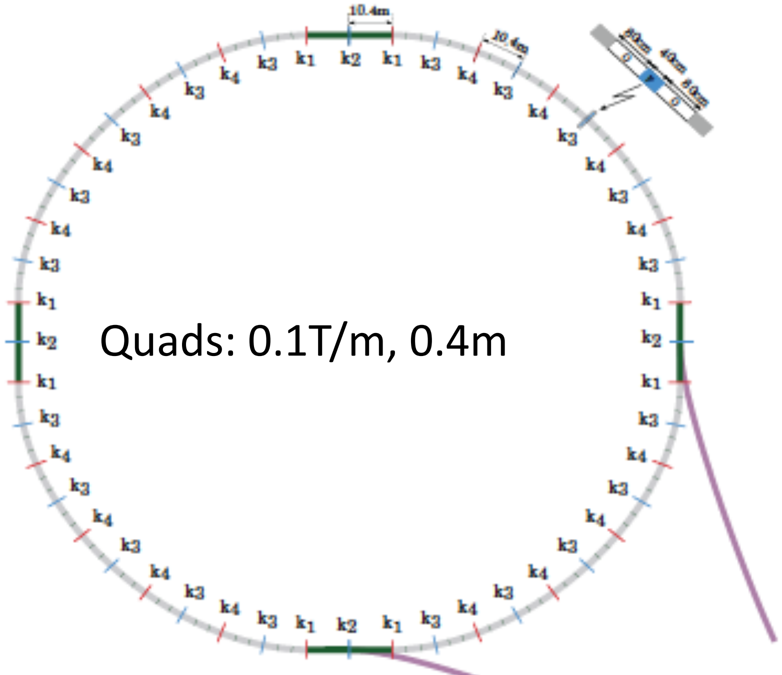
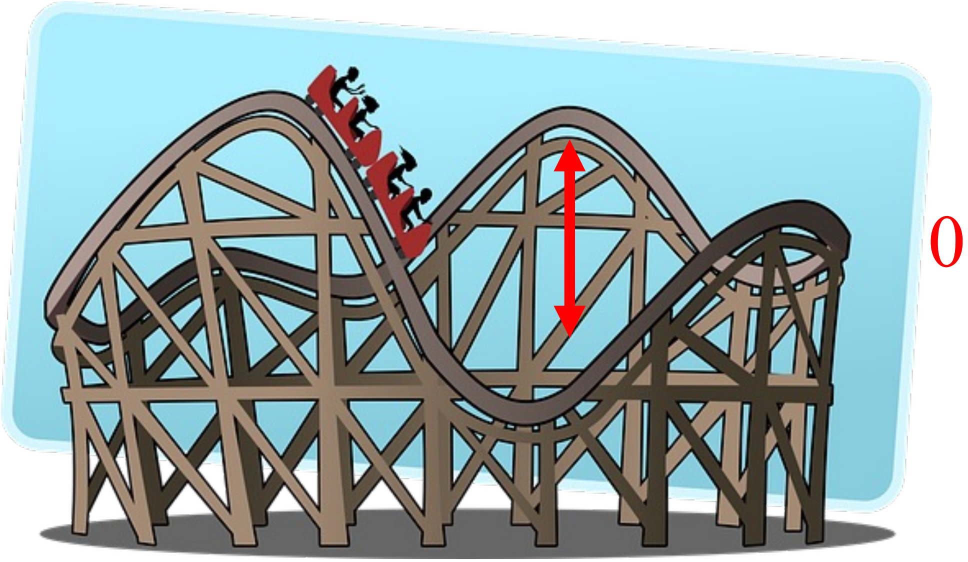


FIG. 8. *Longitudinal polarization case* $S_s = 1$, *CW beam only.* Vertical spin precession rate vs $B_x = 1$ nT field N harmonic around the ring azimuth. The magnetic field amplitude is chosen to be similar to beam separation requirements in Sec. IV A, and more than $B_x = 1$ nT splits the CR beams too much. Irregularities of the low values are due to the inability to determine the exact precession rate from the simulation results. Hence, the points only show a statistical upper limit of the possible vertical precession rate; actual rates could be lower. More about this is in Appendix B.

Ring planarity:
The average vertical speed in deflectors needs to be zero!

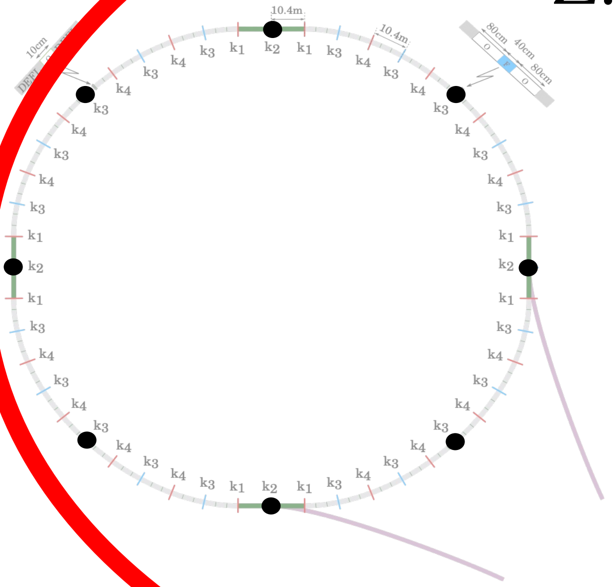


Quads: 0.1T/m, 0.4m

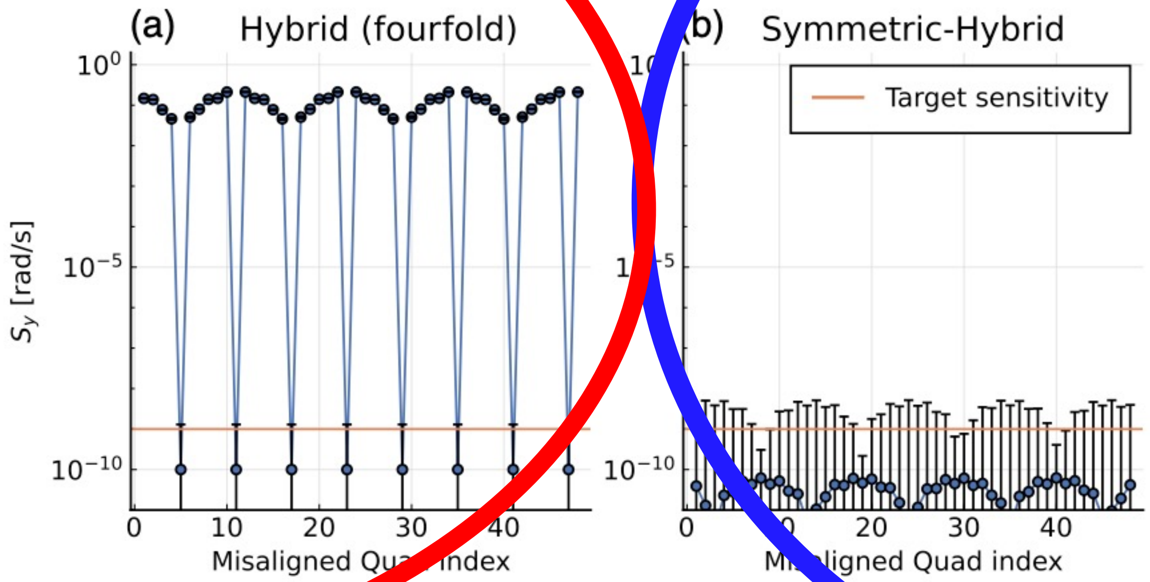


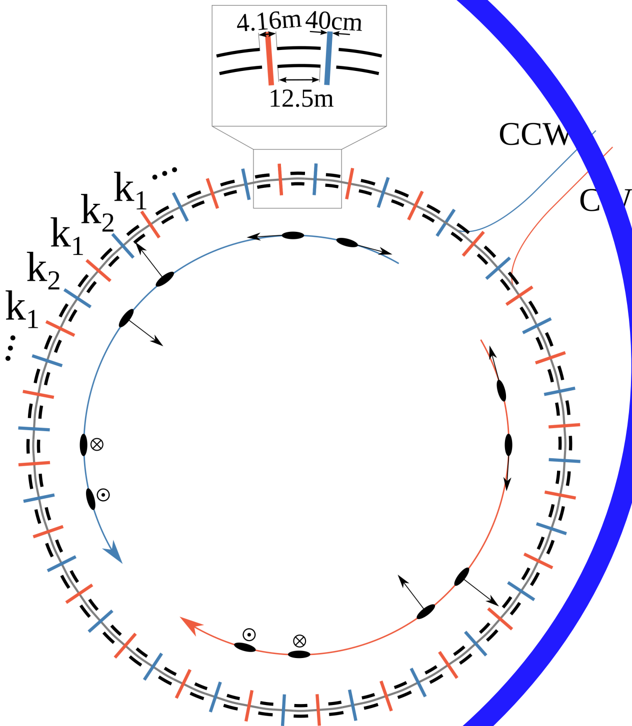
0.1 mm

Hybrid, symmetric lattice storage ring. Great for systematic error reduction.



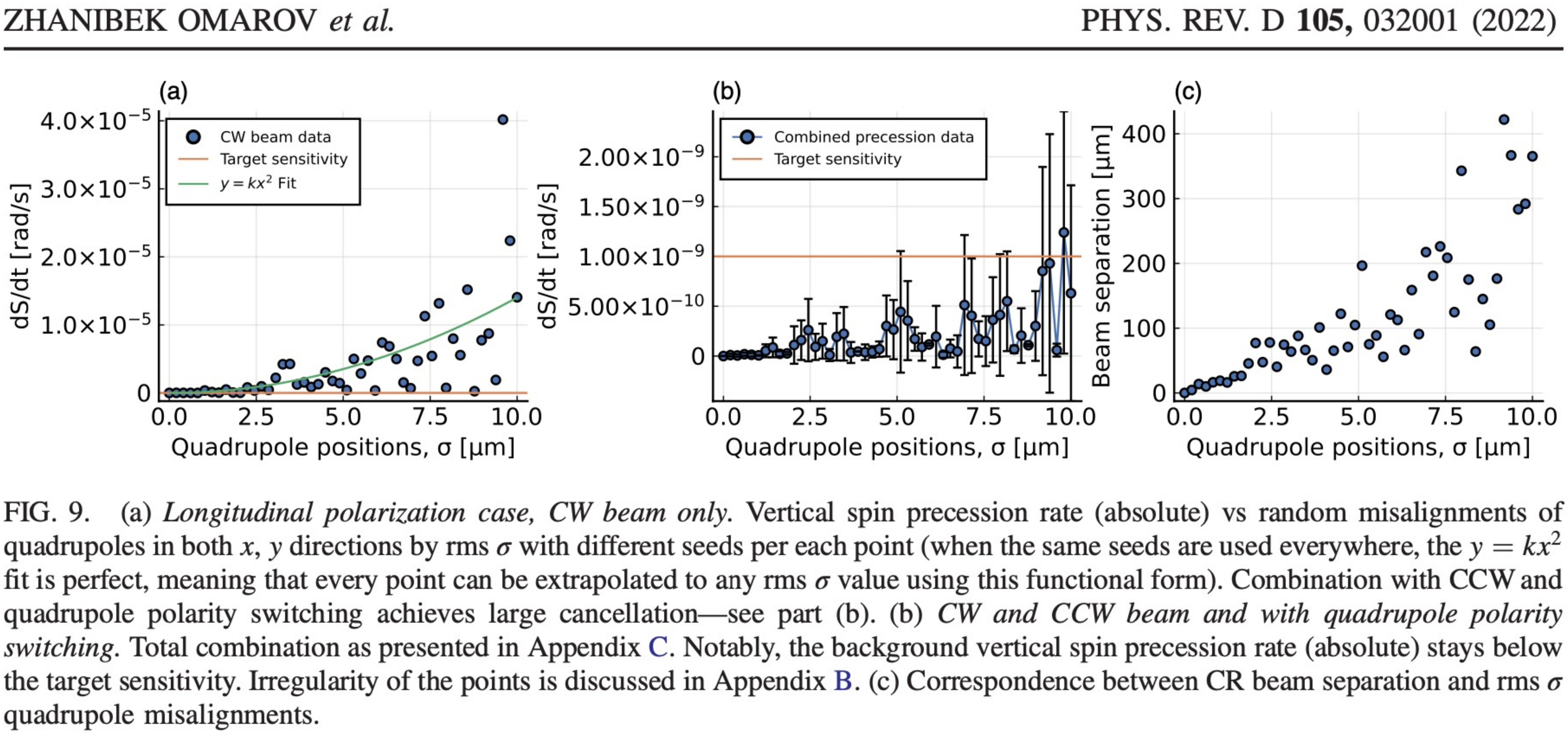
Z. Omarov *et al.*, PHYS. REV. D 105, 032001 (2022)





Sensitivity of radially polarized beam (sensitive to V. Dark Matter/Dark Energy, P. Graham *et al.*, PRD, 055 010, 2021), most sensitive to vertical velocity problem

Vertical velocity effect cancels

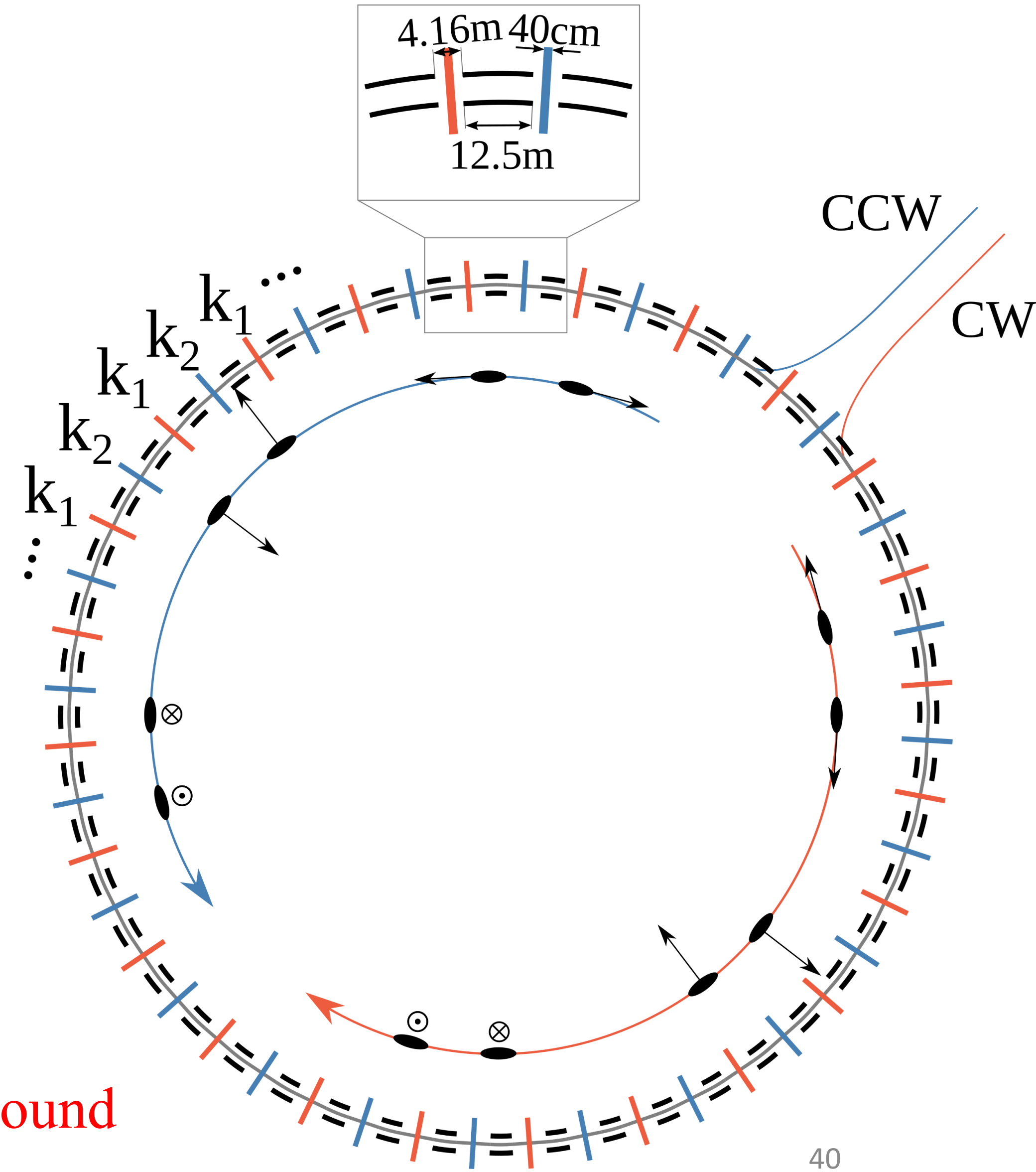


ZHANIBEK OMAROV *et al.* PHYS. REV. D **105,** 032001 (2022)

FIG. 9. (a) *Longitudinal polarization case, CW beam only*. Vertical spin precession rate (absolute) vs random misalignments of quadrupoles in both x, y directions by rms σ with different seeds per each point (when the same seeds are used everywhere, the $y = kx^2$ fit is perfect, meaning that every point can be extrapolated to any rms σ value using this functional form). Combination with CCW and quadrupole polarity switching achieves large cancellation—see part (b). (b) *CW and CCW beam and with quadrupole polarity switching*. Total combination as presented in Appendix C. Notably, the background vertical spin precession rate (absolute) stays below the target sensitivity. Irregularity of the points is discussed in Appendix B. (c) Correspondence between CR beam separation and rms σ quadrupole misalignments.

Conceptual breakthroughs against systematic errors

- Clock-wise (CW) vs. Counter-Clock-Wise (CCW)
  - Eliminates vertical Electric field background
- Hybrid lattice (electric bending, magnetic focusing)
  - Shields against background magnetic fields
- Highly symmetric lattice (24 FODO systems)
  - Eliminates vertical velocity background
- Positive and negative helicity
  - Reduce polarimeter systematic errors
- Flat ring to 0.1 mm, beams overlap within 0.01 mm; Spin-based alignment
  - Geometrical phases; High-order vertical E-field
  - Eliminates effects that depend on a product of two background fields



General approach on systematic errors (1)

- A single parameter, e.g., vertical E-field (E_v) use CW and CCW injections, either simultaneous or consecutive. Adjust the vertical spin precession rate (VSPR) of the CW beam to zero by applying a dipole vertical E-field around the ring.

- Swap the magnet currents at regular intervals.

- Observe and record the horizontal spin precession rate and use it to correct for background signals

General approach on systematic errors (2)

- Effects that depend on a product of two parameters, apply spin-based alignment (Omarov’s method):

- Vary one of the parameters to tune out the other until you observe “zero” slope

- It can be applied to both parameters one after the other.

- Challenge: to come up with all the possible combinations.

Magnetic field specs, exp. running

- The radial magnetic field becomes a problem, only when there is electric focusing in the lattice.

- Apply Omarov's method of spin-based alignment to tune the electric focusing out. The current spec is 1nT for $m<10^{-7}$.

From Zhanibek Omarov's thesis

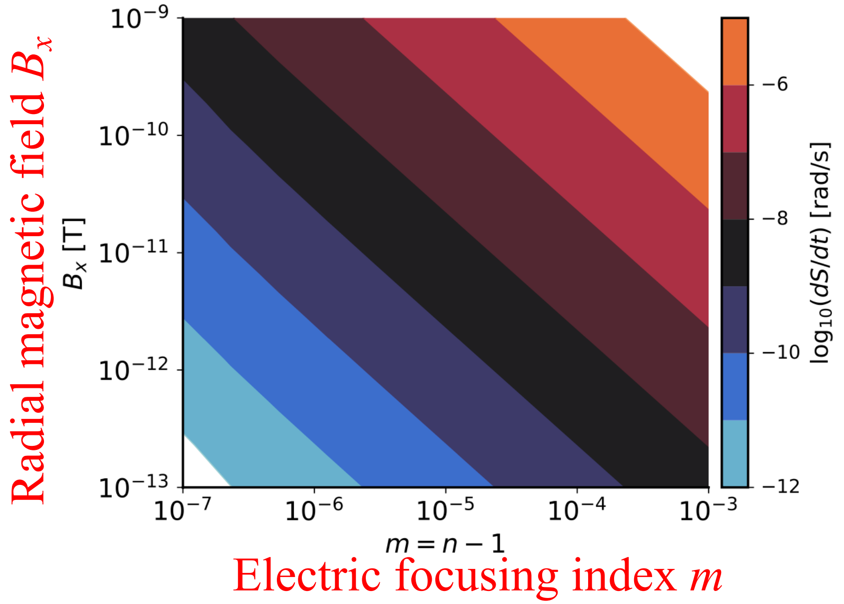


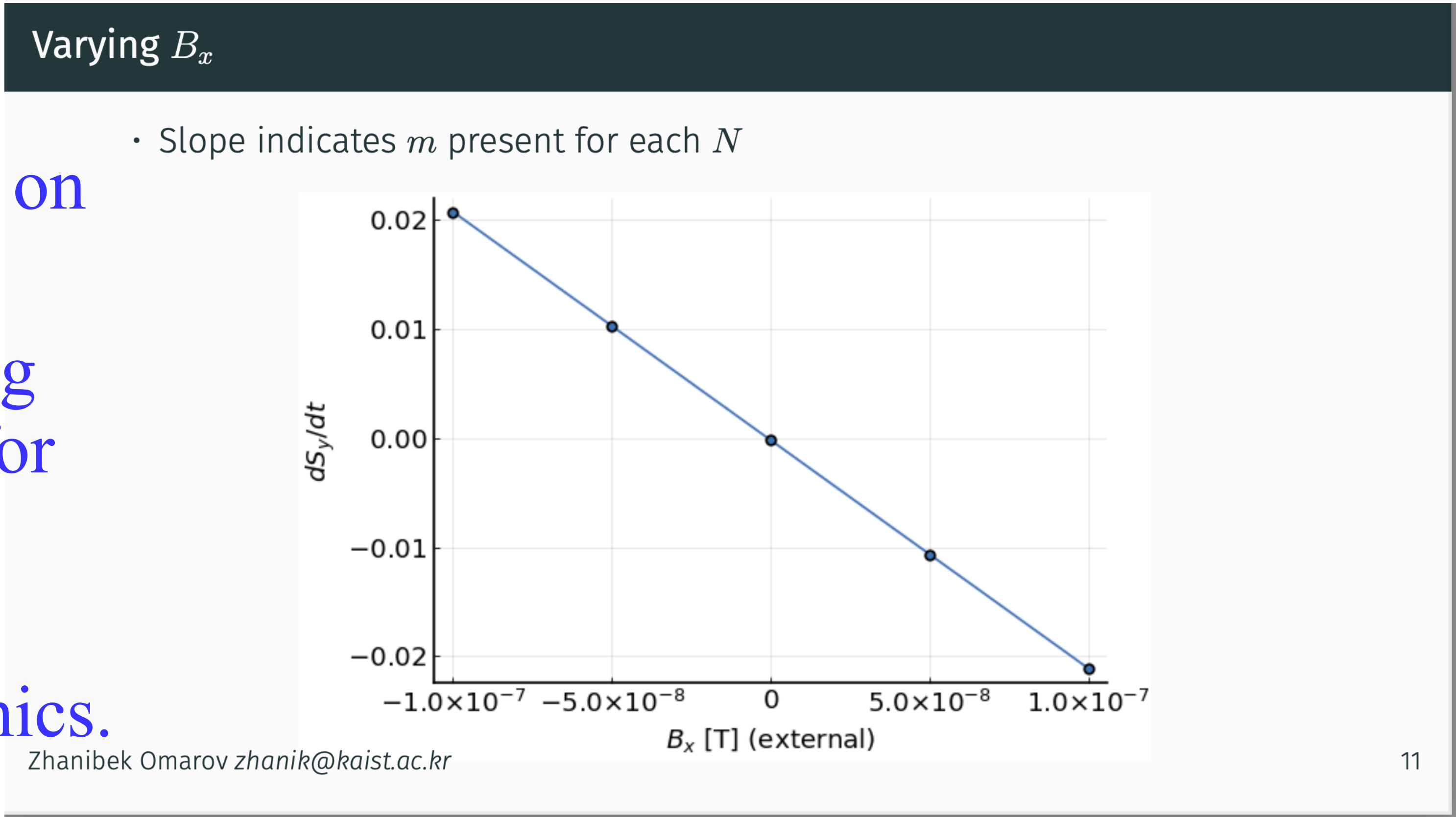
Figure 4.8: Vertical spin precession rate (EDM-like signal) — color scale — as a function of electric focusing index $m = n - 1$ (horizontal axis) and external radial magnetic field B_x (vertical axis). The black color band approximately refers to 1 nrad/s, i.e. the experimental precision requirement, hence the setup should be somewhere below the black band. By changing the external magnetic field B_x (moving along a vertical line on this plot), linear dependence of the vertical spin precession rate on the magnetic field will be observed. This indicates the amount of quadrupole E_y present in the storage ring.

Magnetic field specs, exp. running

- Omarov's method of spin-based alignment to tune the electric focusing out. It can be applied to several classes of systematic errors.

From Zhanibek Omarov's presentation

- Vary the radial B-field (B_x) and observe the VSPR slope.
- The EDM signal does not depend on the value of B_x.
- Tune out the electric field focusing until we get zero slope in VSPR for all B_x harmonics.
- Similarly, apply large electric focusing to tune out all B_x harmonics.



Varying B_x

- Slope indicates m present for each N

Zhanibek Omarov *zhanik@kaist.ac.kr*

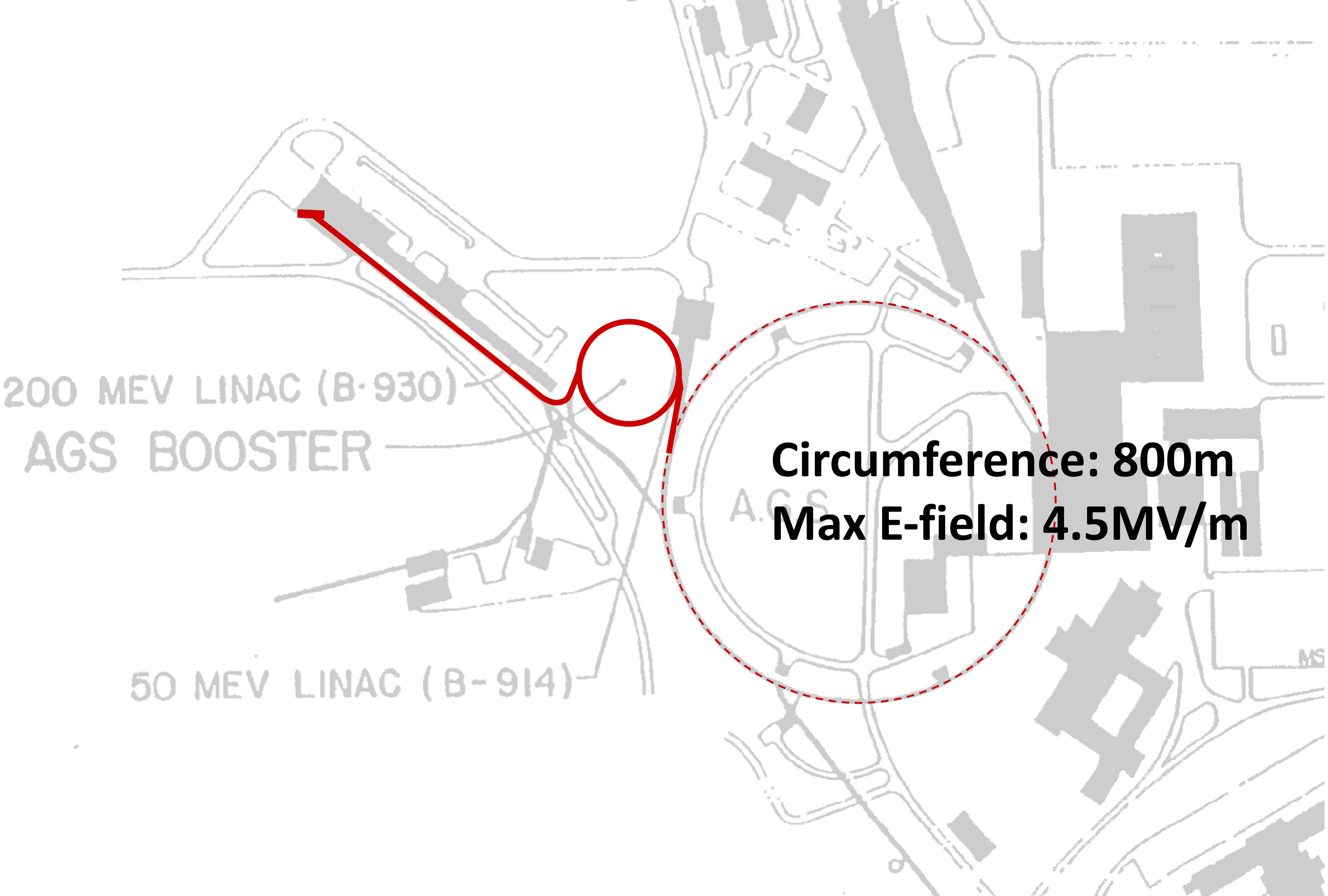
Protons in a hybrid-symmetric ring: no new technology

- No need to develop/test new technology
  - Simultaneous CW/CCW beam storage is possible
  - Electric field ~4.5 MV/m with present technology
  - Magnetic fields from misplaced quads are self-shielded by the magnetic focusing
  - Hybrid/symmetric ring options are simple. Large tune in both planes (strong focusing), beam position monitor (BPM) tasks are achievable with present technology.
  - Estimated SCT are large, injection into ring works, while all primary systematic error sources are kept small.

- After protons, add dipole magnetic field in bending sections:
  - Can do proton, deuteron, ^{3}He, (and muons)

System	Risk factor, comments
Ring construction, beam storage, stability, IBS	Low. Strong (alternate) focusing, a ring prototype has been built (AGS analog at BNL) in 60's. Lattice elements placement specs are ordinary. Intra-beam-scattering (IBS) OK below transition.
E-field strength	Low. Plate-units are similar to those ran at Tevatron with higher specs.
E-field plates shape	Medium. Make as flat as conveniently possible. Probe and shim out high order fields by intentionally splitting the CR-beams
Spin coherence time	Low. Ordinary sextupoles will provide $>10^3$s.
Beam position monitors (BPM), SQUID-based BPMs.	Medium. Ordinary BPMs and hydrostatic level system (HLS) to level the ring to better than 0.1mm; SQUID-based or more conventional BPMs to check CR-beams split to 0.01mm.
High-precision, efficient software	Low. Cross-checking our results routinely
Polarimeter	Low. Mature technology available

The proton EDM in the AGS tunnel at BNL



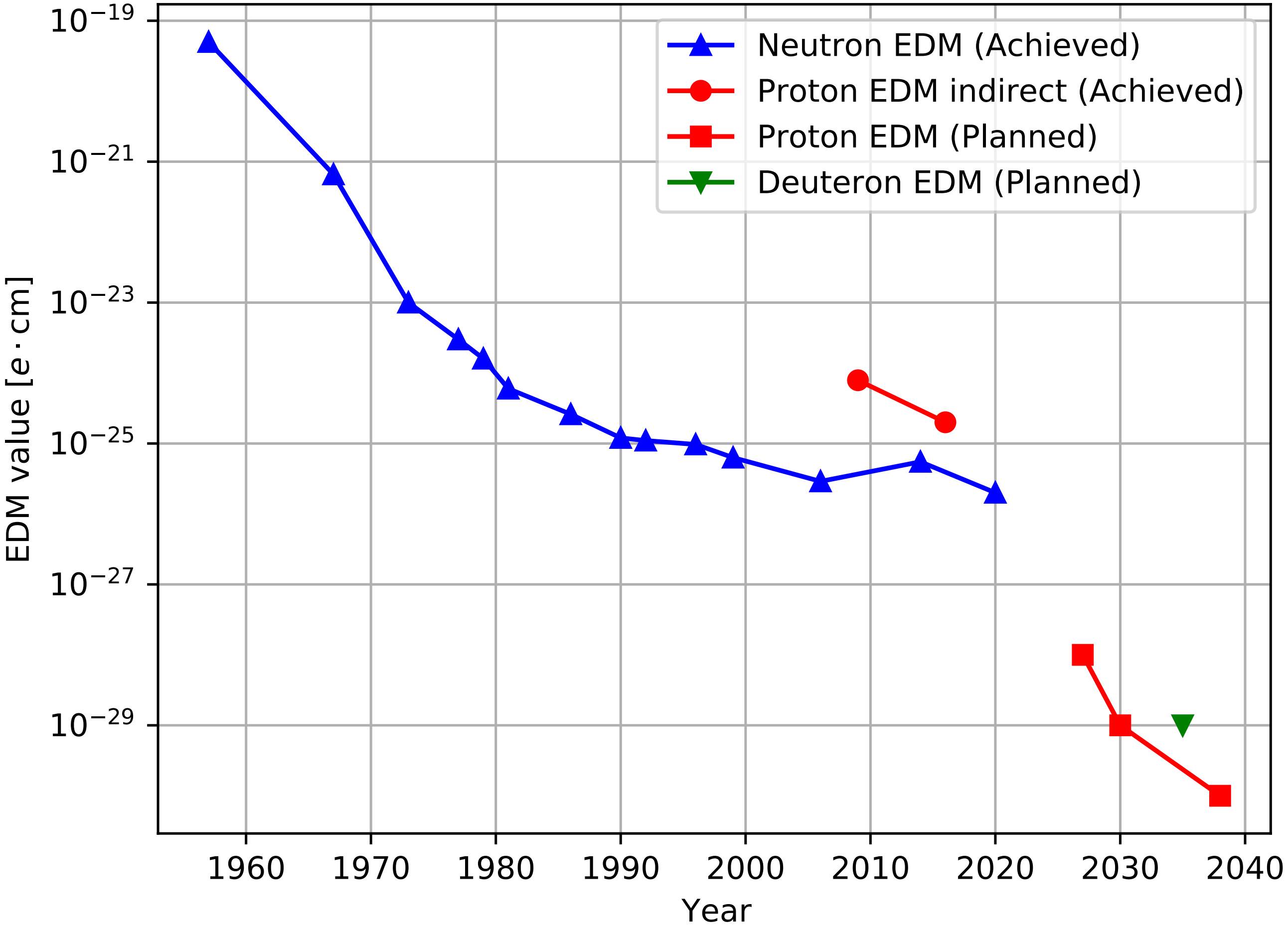
Circumference: 800m

Max E-field: 4.5MV/m

John Benante, Bill Morse in AGS tunnel, plenty of room for the EDM ring.

Timeline

- Snowmass/white paper, CDR, proposal/TDR, prototype/string-test, ring construction (3-5 years), storage (2-3 years) to first publication
- Effort similar to muon g-2 experiments.
- Possible interesting results within a decade.



Summary

- Turkish scientists have made world-class contributions to world-class physics. I am very proud to call them my colleagues

- We have received encouragement from Snowmass to write a technically advanced report for an experiment at AGS.
    - We can have first interesting results within the decade
    - 10^{-29}*e*-cm for the proton within ten years from start
    - 10^{-29}*e*-cm for the deuteron, ^{3}He within five years afterwards

- Funding is a necessary condition but alone not sufficient to arrive at this level. We've invested in human capacity for innovation and ability to do the impossible → possible by hard work.

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14. G.W. Bennett *et al.,* An improved limit on the muon electric dipole moment, Phys. Rev. D 80, 052008 (2009)
15. F.J.M. Farley *et al.,* A new method of measuring electric dipole moments in storage rings, Phys. Rev. Lett. 93, 052001 (2004)
16. …

Extra slides

On Kim's slide from his Snowmass talk

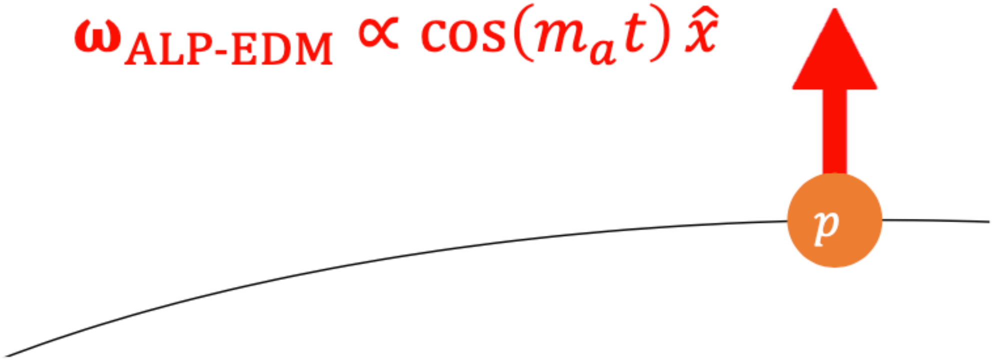
Storage ring probes of DM/DE

- Couplings with dark matter (DM) and dark energy (DE)

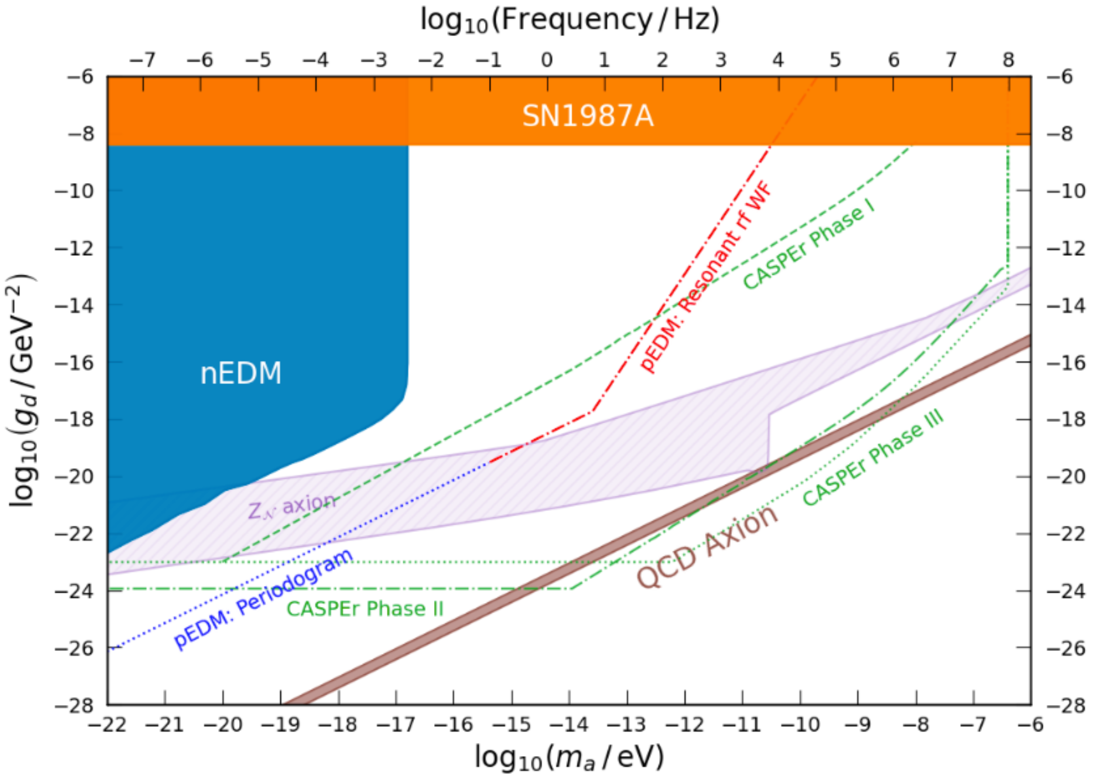
P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
P. Graham et al., PRD **103**, 055010 (2021)

  - ALP-EDM $(g_{aN\gamma} a \hat{\sigma}_N \cdot \mathbf{E}) \Rightarrow$ oscillating EDM at m_a. For the QCD axion: $d_N^{\mathrm{QCD}} \approx 10^{-34} \cos(m_a t)\ e \cdot \mathrm{cm}$.

$\boldsymbol{\omega}_{\text{ALP-EDM}} \propto \cos(m_a t)\, \hat{x}$



ALP-EDM coupling



- Storage ring probes of axion-induced oscillating EDM.
  S. Chang *et al.*, PRD **99**, 083002 (2019).
- Complementary method using an rf Wien filter.
  On Kim and Y. Semertzidis, PRD **104**, 096006 (2021)
- Parasitic measurement with pEDM experiment.
  - Low frequency: Periodogram analysis. The best sensitivity!
  - High frequency: Resonant rf Wien filter.

Classification of systematic errors at 10^{-29} *e*-cm for hybrid-symmetric lattice

✓Alternate magnetic focusing allows simultaneous CW & CCW storage and shields against external B-fields. Vertical dipole E-fields eliminated (its own "co-magnetometer"), unique feature of this lattice.

✓Symmetric lattice significantly reduces systematic errors associated with vertical velocity (major source). Using longitudinal, radial and vertical polarization directions, sensitive to different physics/systematic errors.

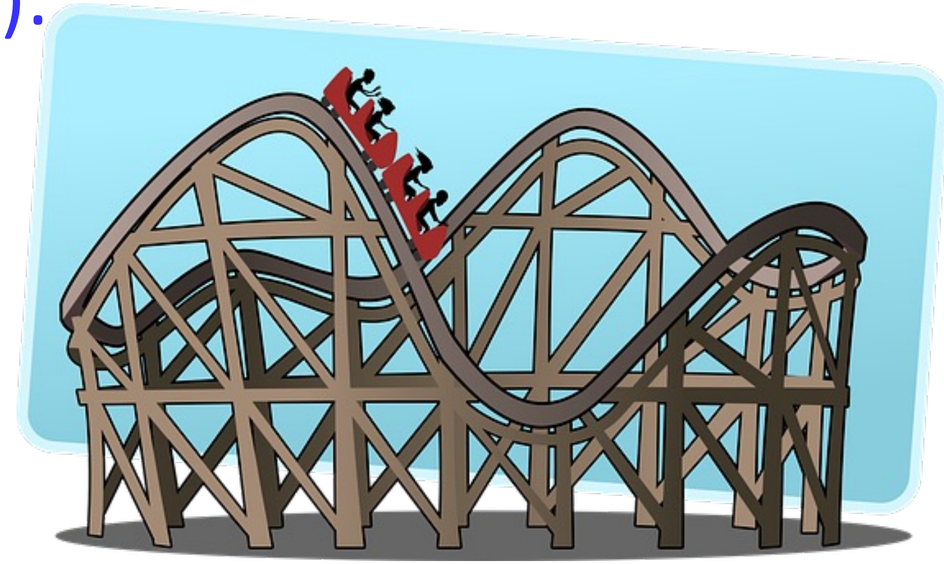
✓Required ring planarity <0.1mm; CW & CCW beam separation <0.01mm, resolves issues with geometrical phases

Ring planarity critical to control geometrical phase errors

- Numerous studies on slow ground motion in accelerators, Hydrostatic Level System for slow ground motion studies at Fermilab. (Part of the linear collider studies!)

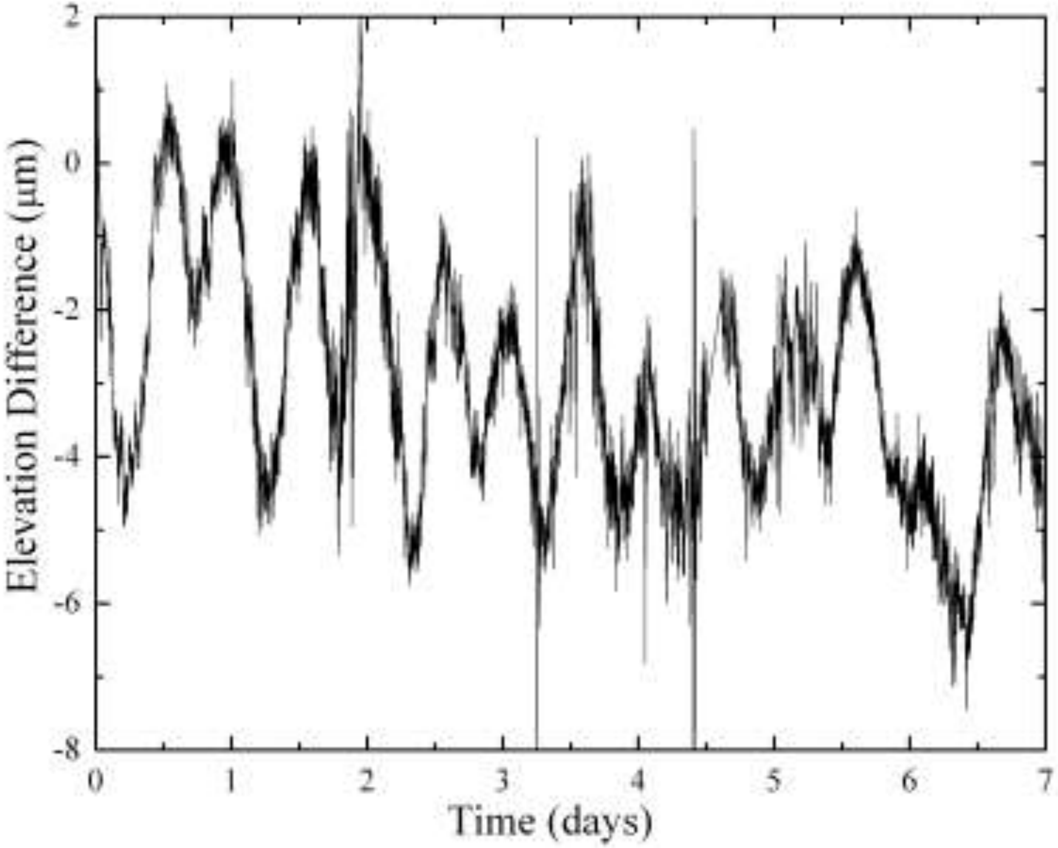
- Thorough review by Vladimir Shiltsev (FNAL):

https://arxiv.org/pdf/0905.4194.pdf



HLS measurements at Fermilab

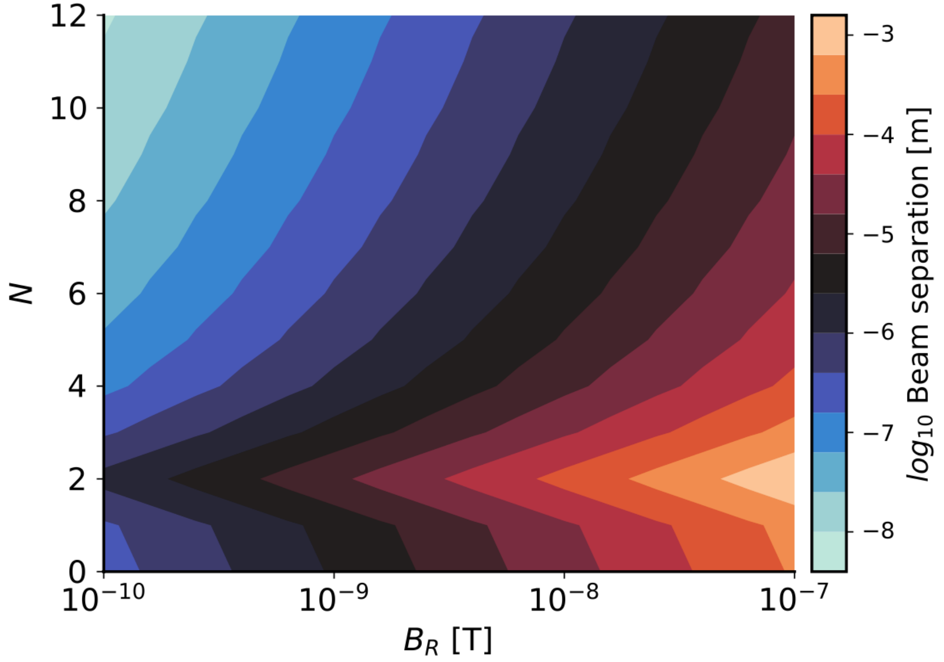
Fig.35. HLS probe on Tevatron accelerator focusing magnet.



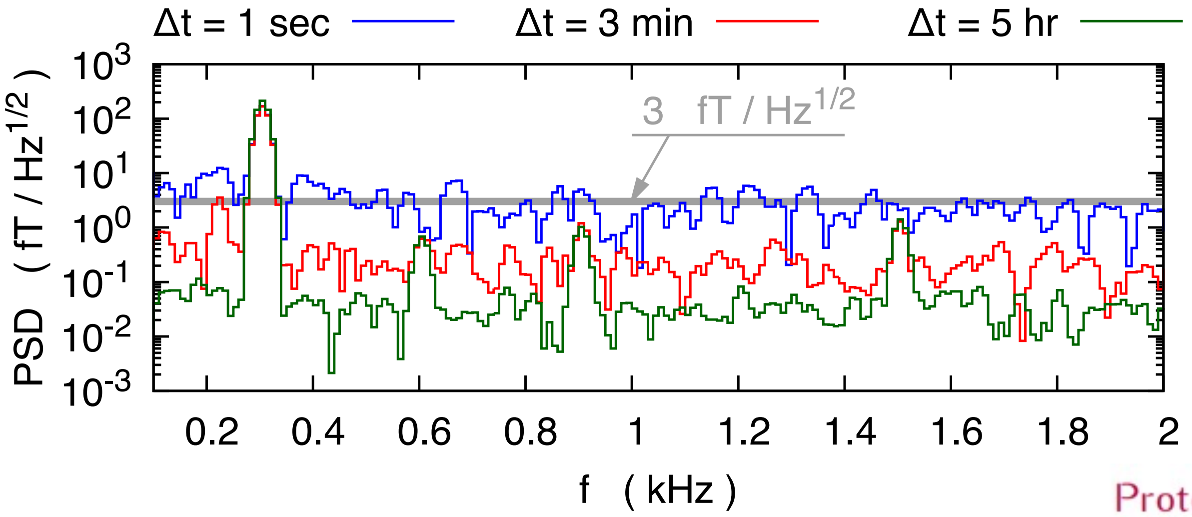
Magnetic field specs, beam storage

- First care should be beam-storage.
- Assuming we want closed-orbit distortion of less than mm level, then the limit should be 100nT (1mG) for the *N*=2 harmonic around the ring.
- The magnetic quads are 40cm long and have a strength of about 0.2 T/m. Therefore, their placement should be at the x=100nT/(0.2T/m)/(0.4m/16m)~0.02m. Since we have 48 quads, we could aim for ~0.1mm level each.
- They should also have the function to either move or apply a compensating dipole vertical and horizontal B-field.

From Zhanibek Omarov's thesis



SQUID-based BPMs, Korea



Next: Testing the concept at an accelerator in Korea.
Issue: Our severe budget reduction doesn't allow it.
We have been invited by Fermilab to test it there in 2022.

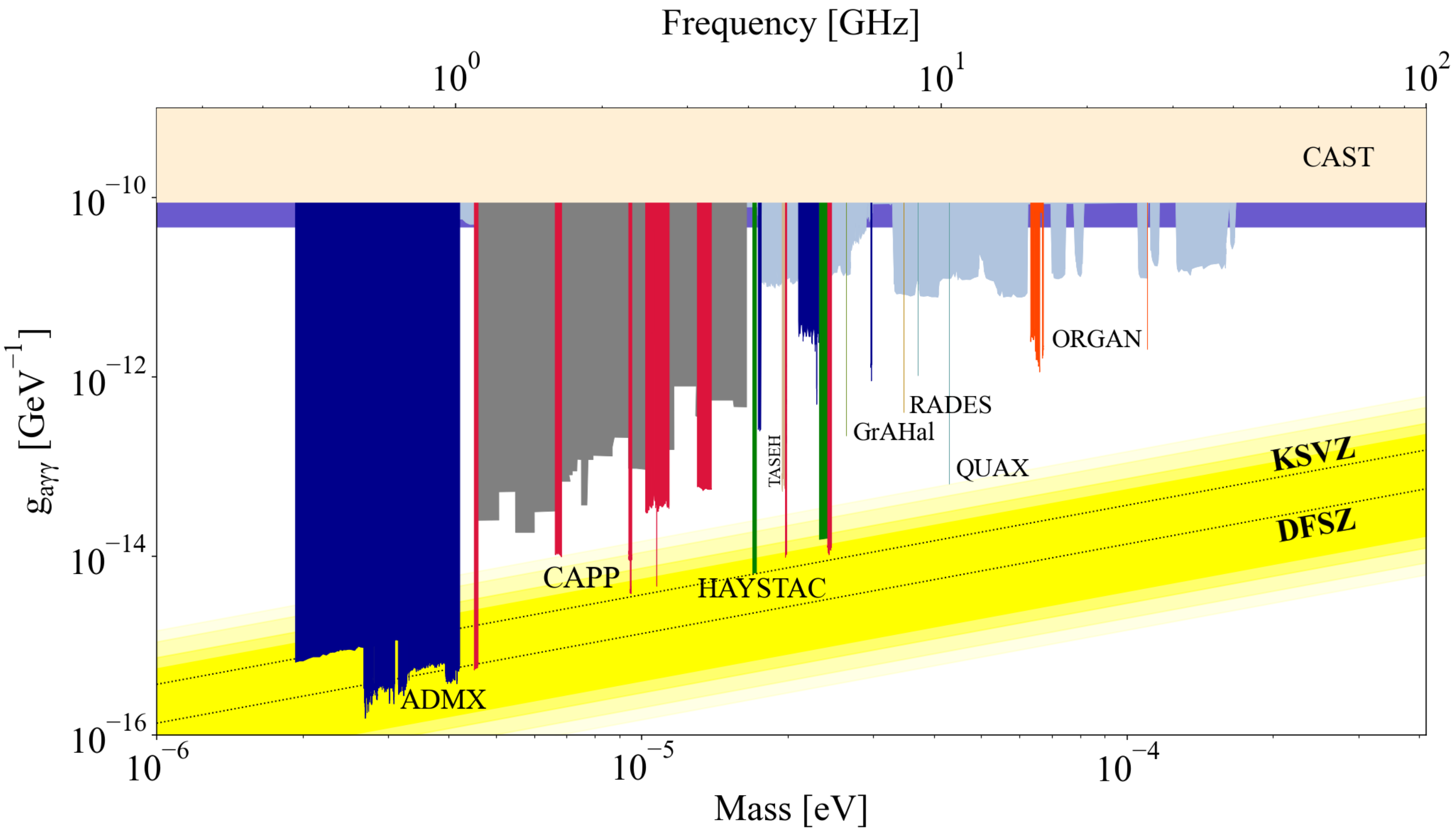
Prototype

- The new design is to be delivered by summer
- Will be 2fT$\sqrt{\text{Hz}}$
- We will make wire tests in Korea
- Would be good to test here at COSY

Selcuk Haciomeroglu, IBS-CAPP

CAPP's axion dark matter search is world-class (red)

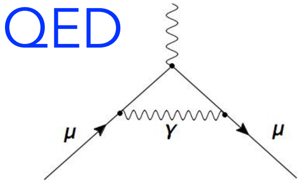
- In large part due to Caglar Kutlu's work on the JPAs (best systems in the world).
- Our recent DFSZ accomplishment is just the beginning



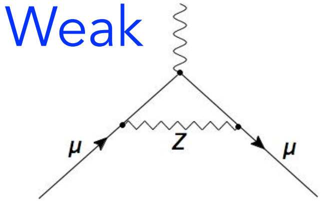
Muon g-2: SM contributions

$$\boxed{a_\mu = a_\mu(\text{QED}) + a_\mu(\text{Weak}) + a_\mu(\text{Hadronic})}$$

- **Theory :**

QED


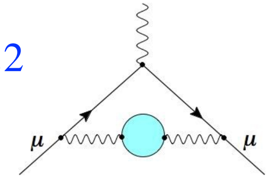
$+\ldots$ $116\,584\,718.9\,(1) \times 10^{-11}$ 0.001 ppm

Weak


$+\ldots$ $153.6\,(1.0) \times 10^{-11}$ 0.01 ppm

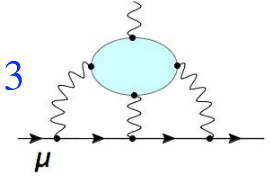
Hadronic…

…Vacuum Polarization (HVP)

α^2


$+\ldots$ $6845\,(40) \times 10^{-11}$ [0.6%] 0.37 ppm

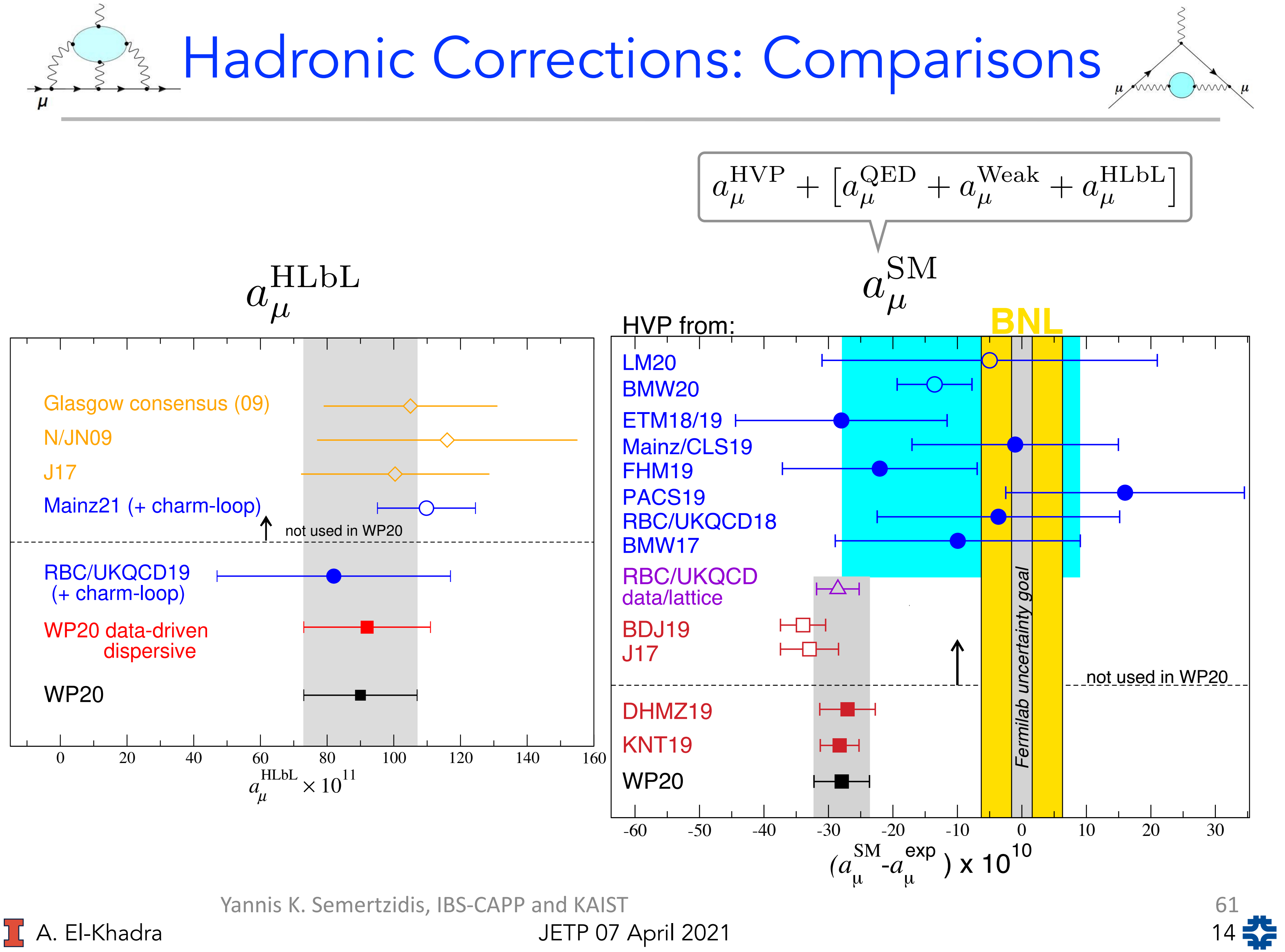
…Light-by-Light (HLbL)

α^3


$+\ldots$ $92\,(18) \times 10^{-11}$ [20%] 0.15 ppm

Muon g-2 announcement, theory vs. theory

- Theory :



Hadronic Corrections: Comparisons

$$a_\mu^{\mathrm{HVP}} + [a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{Weak}} + a_\mu^{\mathrm{HLbL}}]$$

$$a_\mu^{\mathrm{SM}}$$

$$a_\mu^{\mathrm{HLbL}}$$

A. El-Khadra

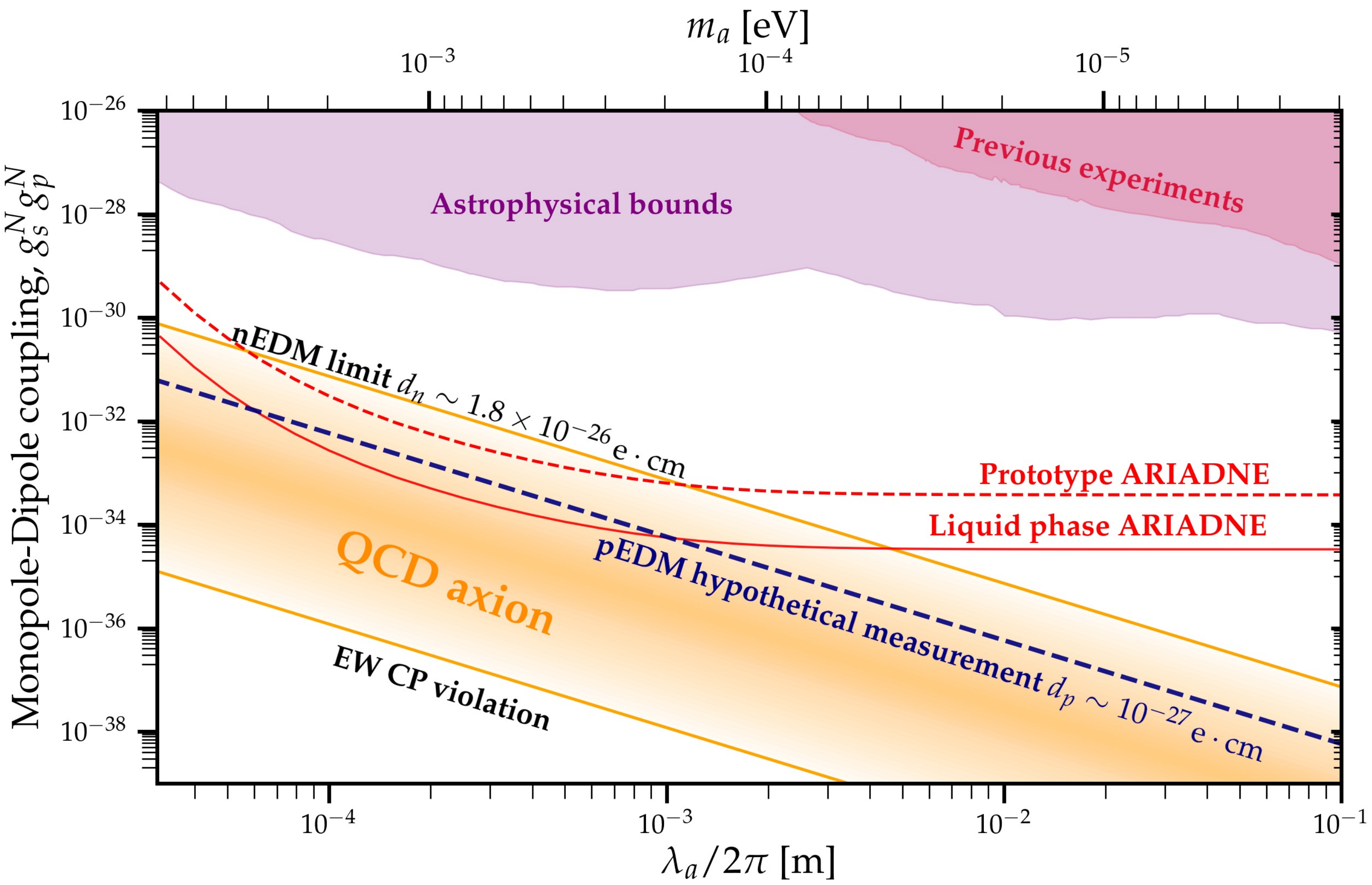
JETP 07 April 2021

14

Large Surface Area Electrodes

Parameter	Tevatron pbar-p Separators	BNL K-pi Separators	pEDM (low risk)
Length/unit	2.6m	4.5m	5 × 2.5m
Gap, E-field	5cm, 7.2 MV/m	10cm, 4 MV/m	4cm, 4.5 MV/m
Height	0.2m	0.4m	0.2m
Number	24	2	48
Max. HV	±(150-180)KV	±200KV	±90KV

ARIADNE and nucleon EDMs

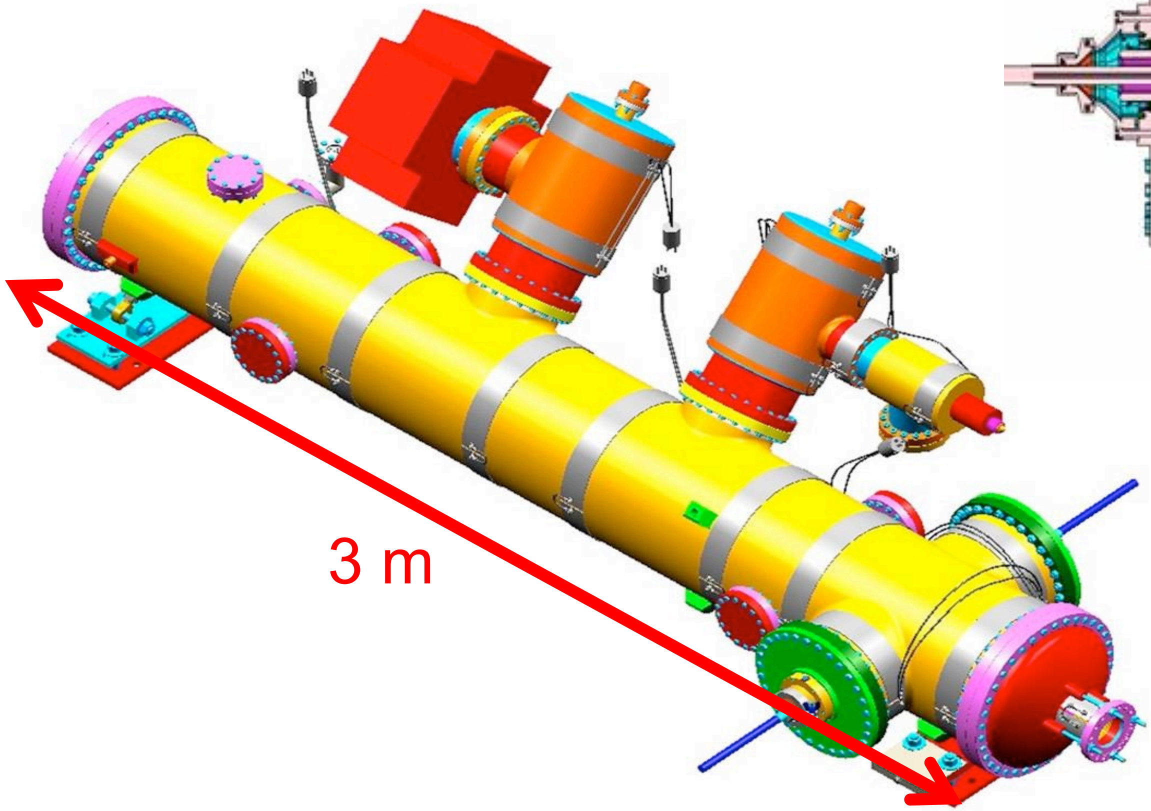


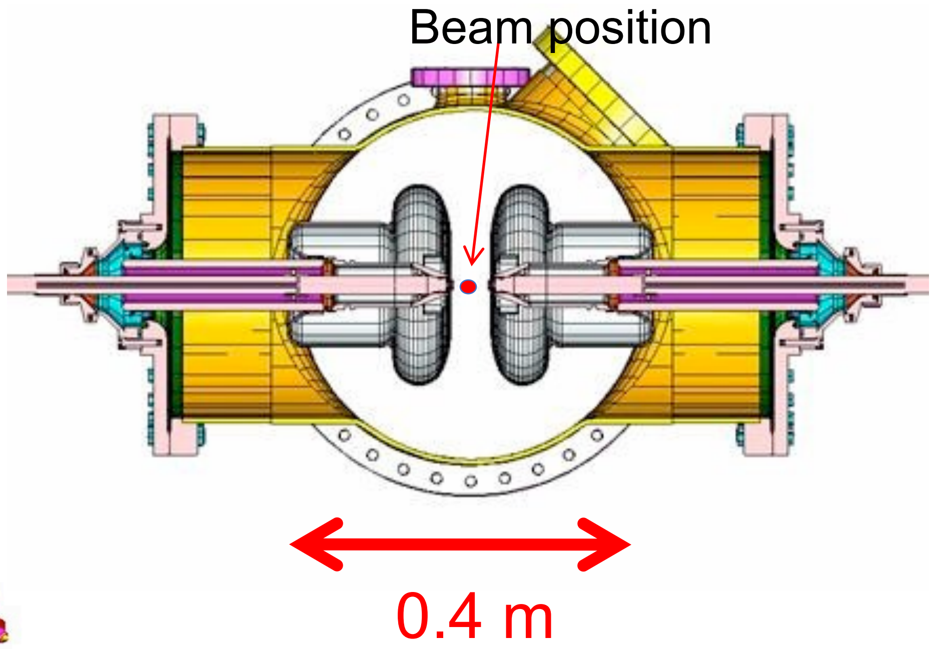
Y. K. Semertzidis and S. Youn. , 2104.14831

- Combine with ARIADNE and nucleon EDM provides decisive information
- Scenario:
  - ARIADNE: Null axion
  - pEDM measure: $d_p \sim 10^{-27} \mathrm{e} \cdot \mathrm{cm}$
  - Exclude QCD axion independent of axion DM:

$$0.2\ \mathrm{meV} \lesssim m_a \lesssim 3\mathrm{meV}$$

E-field plate modules: The (24) FNAL Tevatron ES-separators ran for years with harder specs





Polarimeter analyzing power at P_{magic} is great

Analyzing power can be further optimized

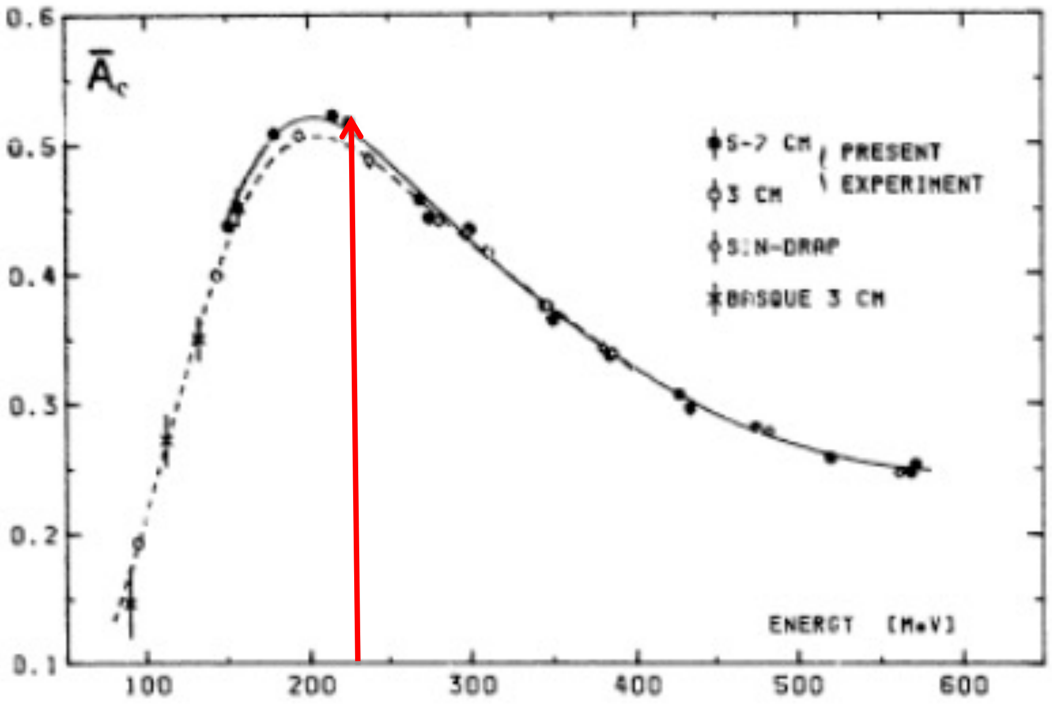
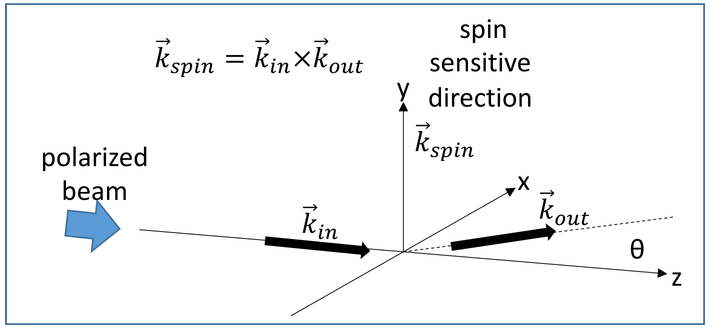
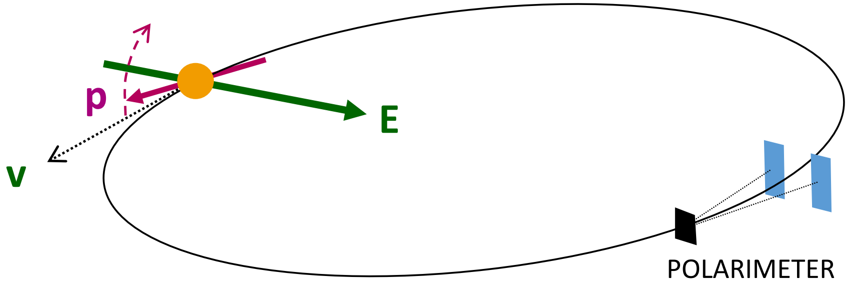


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

Fig.4. The angle averaged effective analyzing power as a function of the proton kinetic energy. The magic momentum of 0.7GeV/c corresponds to 232MeV.





Spin Coherence Time

- Not all particles have same deviation from magic momentum, or same horizontal and vertical divergence (second order effects)

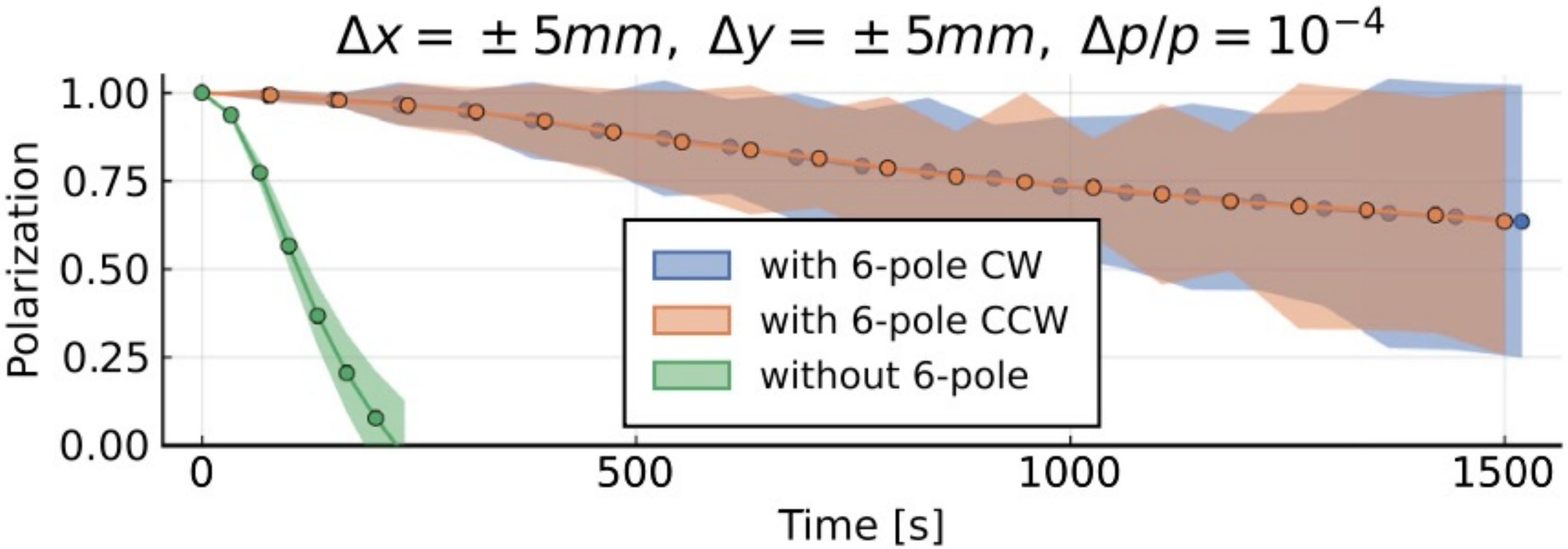
- They Cause a spread in the g-2 frequencies:

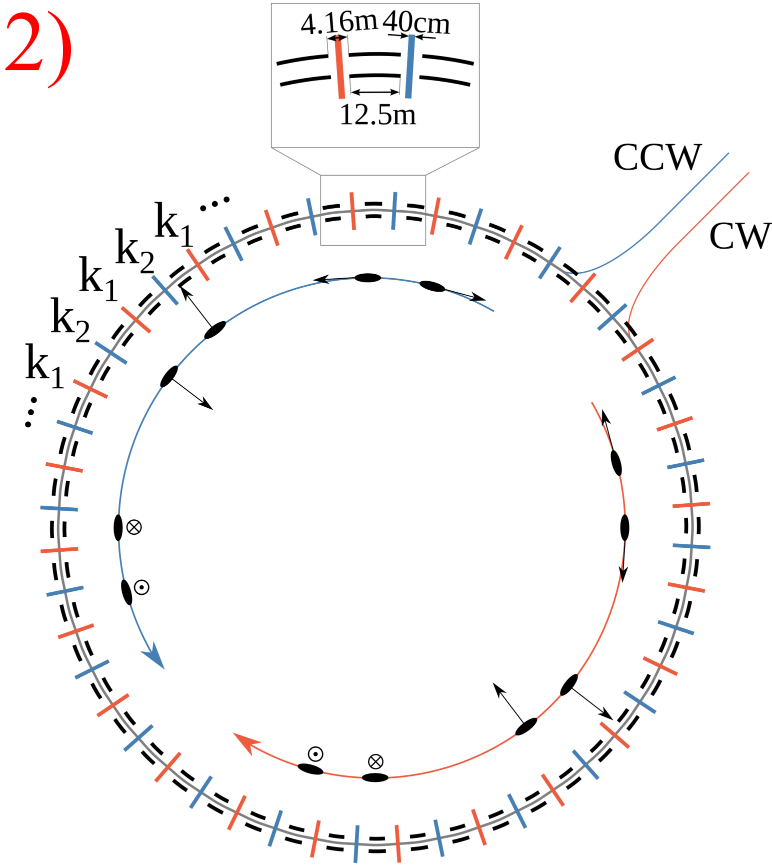
$$d\omega_a = a\vartheta_x^2 + b\vartheta_y^2 + c\left(\frac{dP}{P}\right)^2$$

- Correct by tuning plate shape/straight section length plus fine tuning with sextupoles (current plan) or cooling (mixing) during storage (under evaluation).

Hybrid, symmetric lattice storage ring. Spin Coherence Time with sextupoles

Z. Omarov *et al.*, PHYS. REV. D **105**, 032001 (2022)

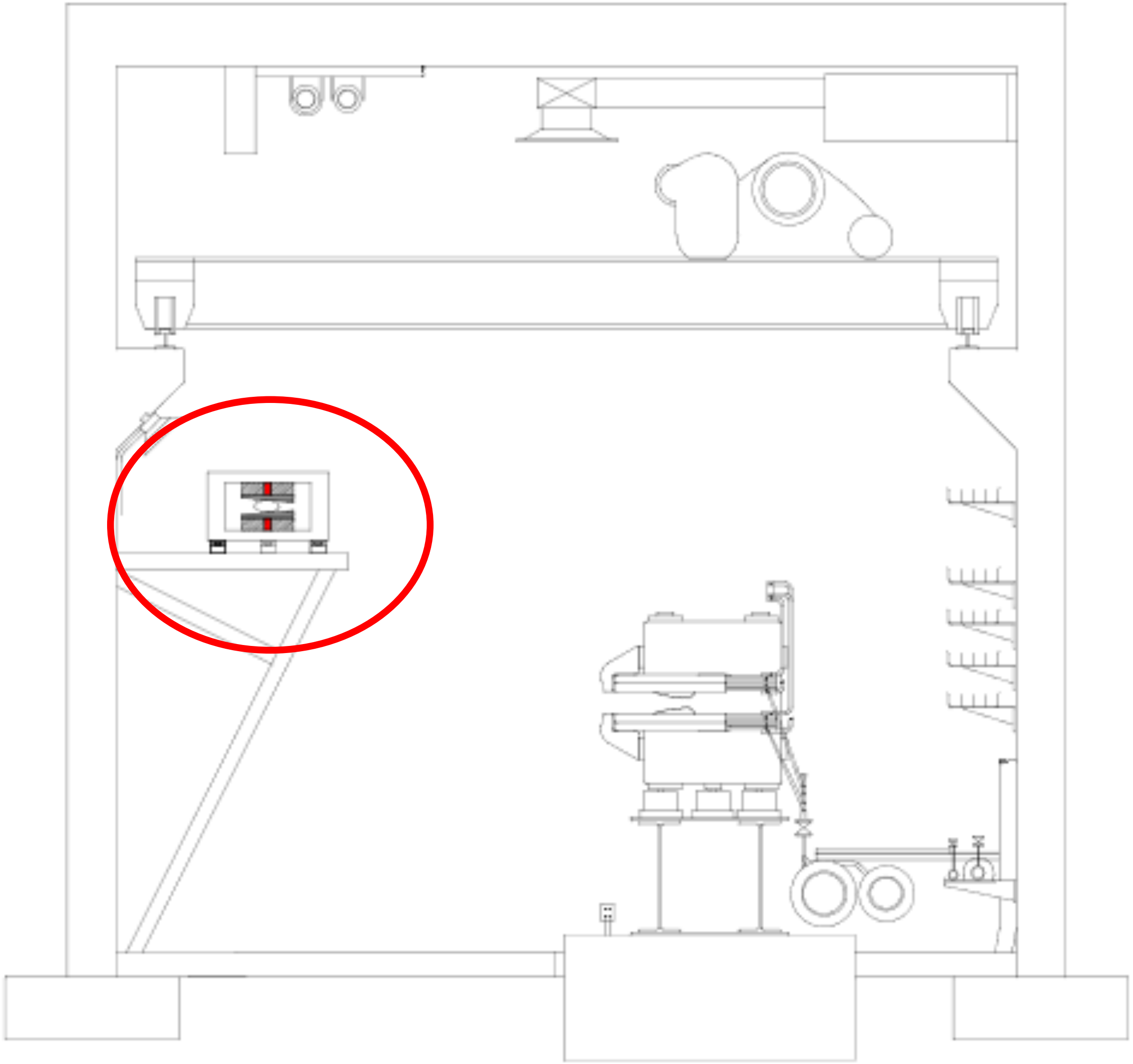


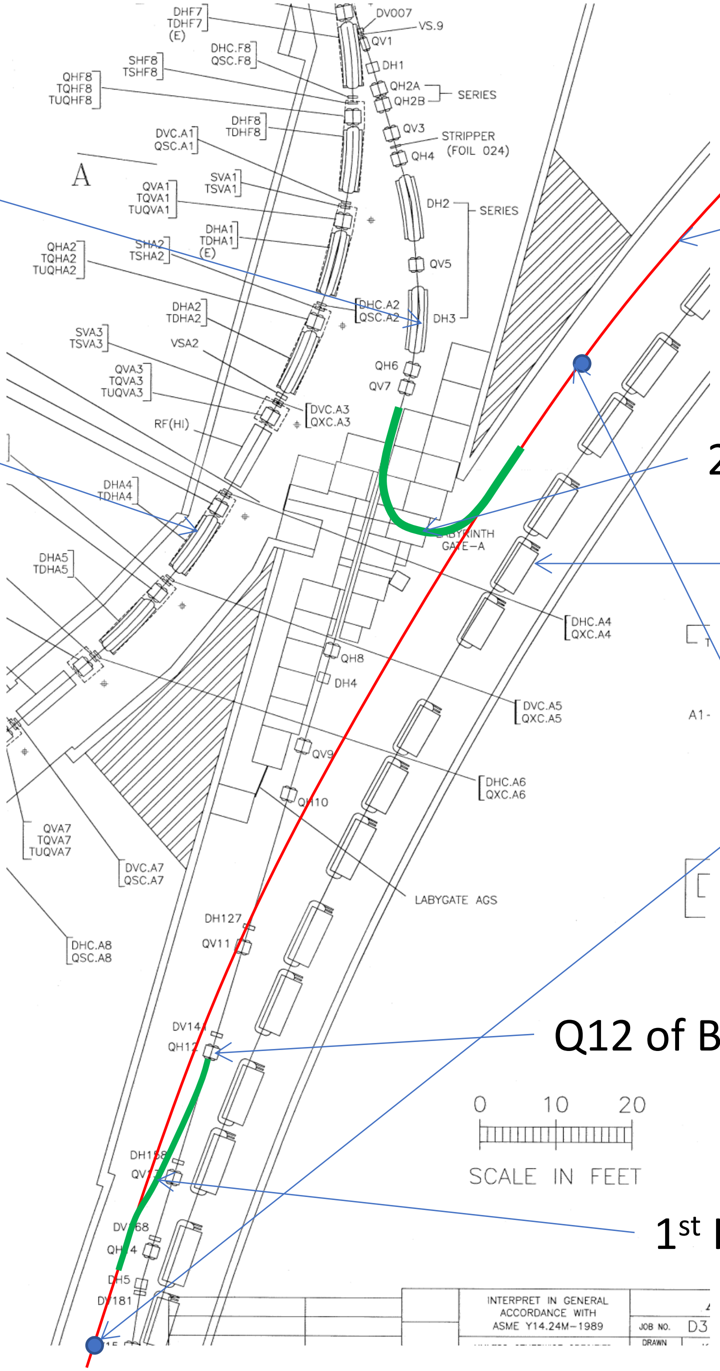


Hybrid (magnetic and elecric) sextupoles were used to achieve long SCT.

Sketch of the AGS Accumulator Ring

- It was sketched for 1.5GeV ring. Space needed: 1mX1m.





Booster-to-AGS BtA

Booster

Proposed EDM Ring

2nd Inj. Line

AGS

Beam Injection points

Q12 of BtA

1st Inj. Line

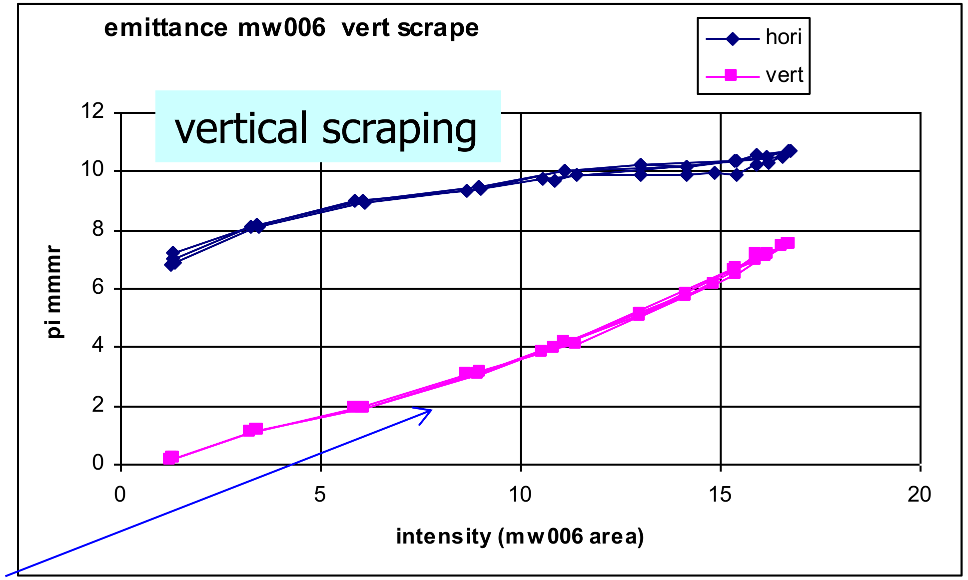
Emittance out of Booster

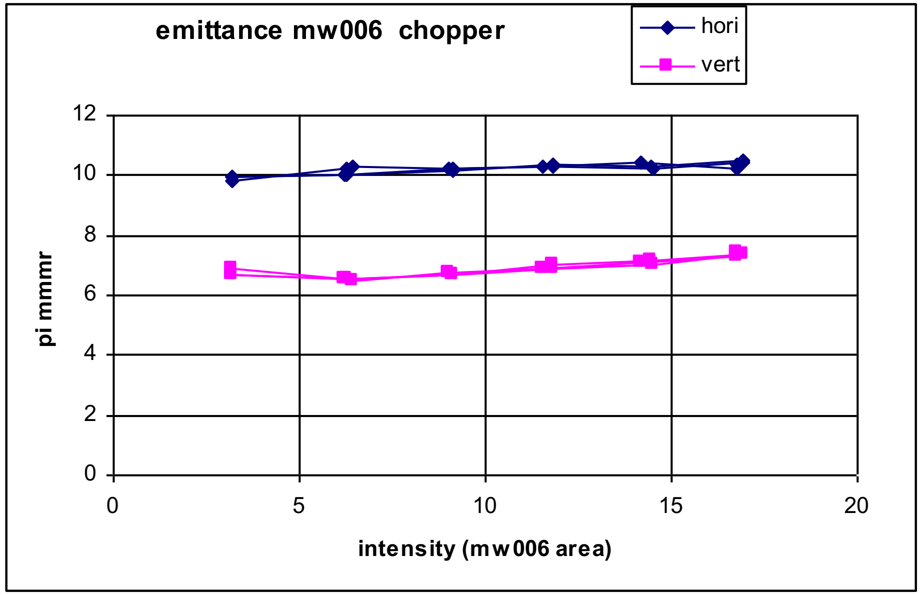
These intensity scan was done in 2009 with Booster input $3*10^{11}$. Not much horizontal scan was done since then. The vertical scale is normalized 95% emittance.

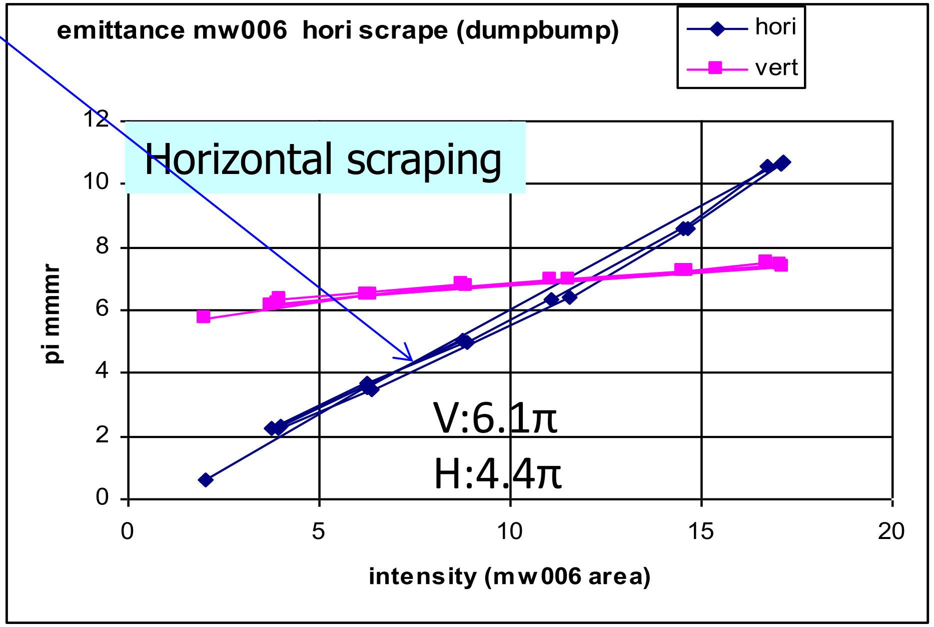
The corresponding normalized rms emittance at 10^{11} is 0.7π horizontal, 1.0π vertical for horizontal scraping.

Intensity: 15~2e11 protons

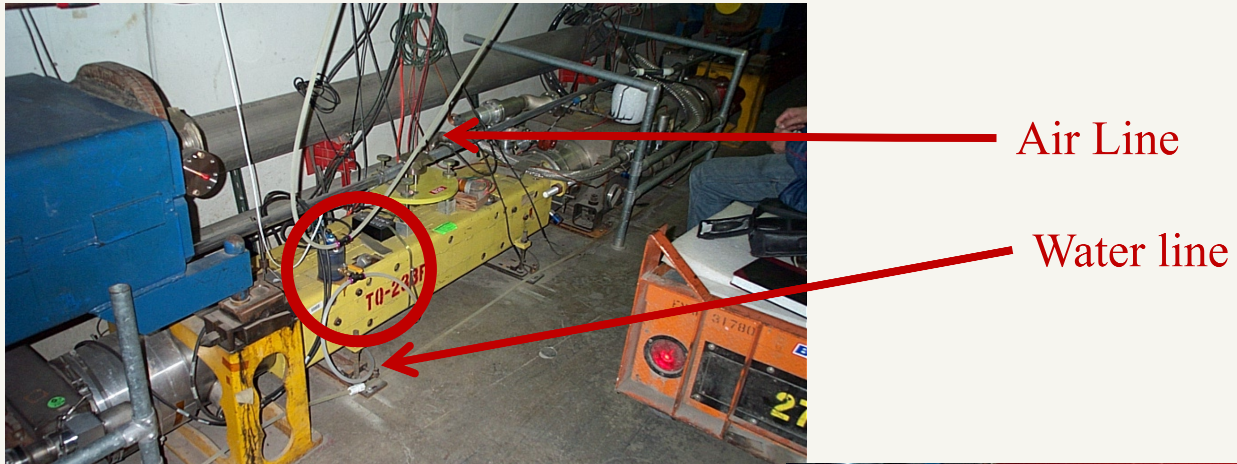
@10^{11}





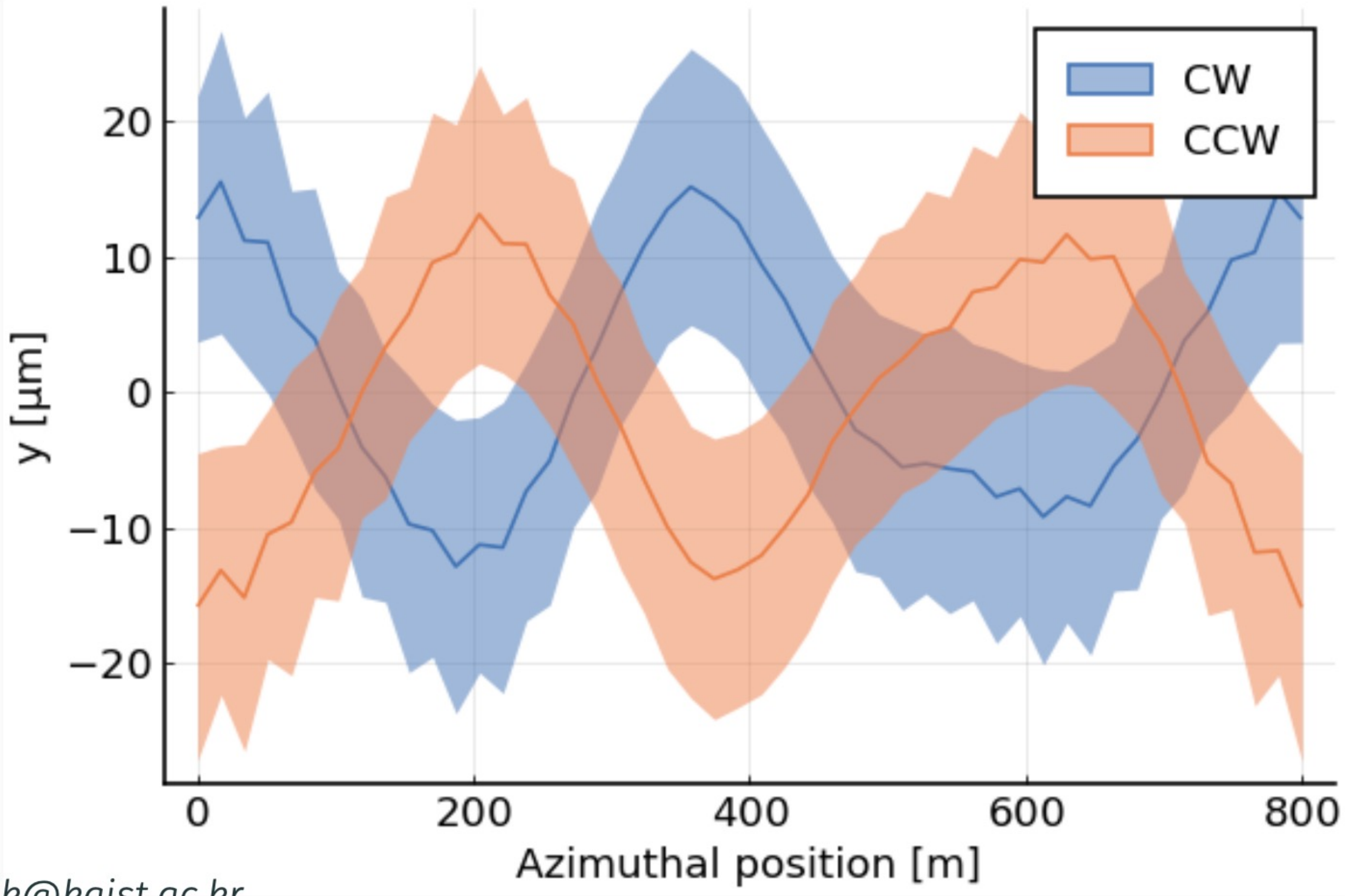


Tevatron Sensors on Quad



In the circle is a water level pot on a Tevatron quadrupole

- Misalign quadrupoles randomly:



Electric quad-field

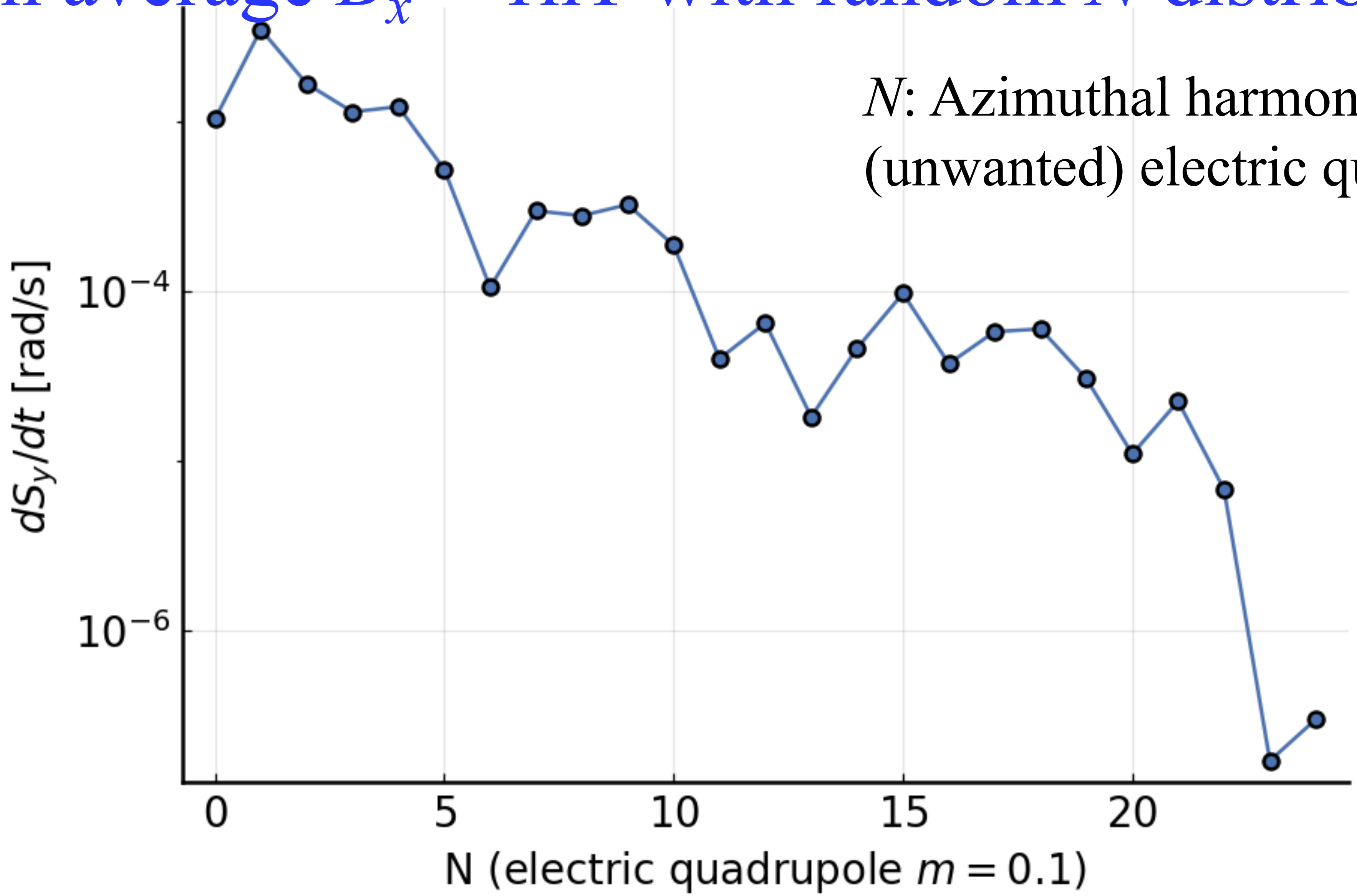
Quantifying E quad

- Using $m = n - 1$ focusing value of deflectors

$$E_y = \left(\frac{E_0(n-1)}{R_0}\right)y = \left(\frac{E_0 m}{R_0}\right)y$$

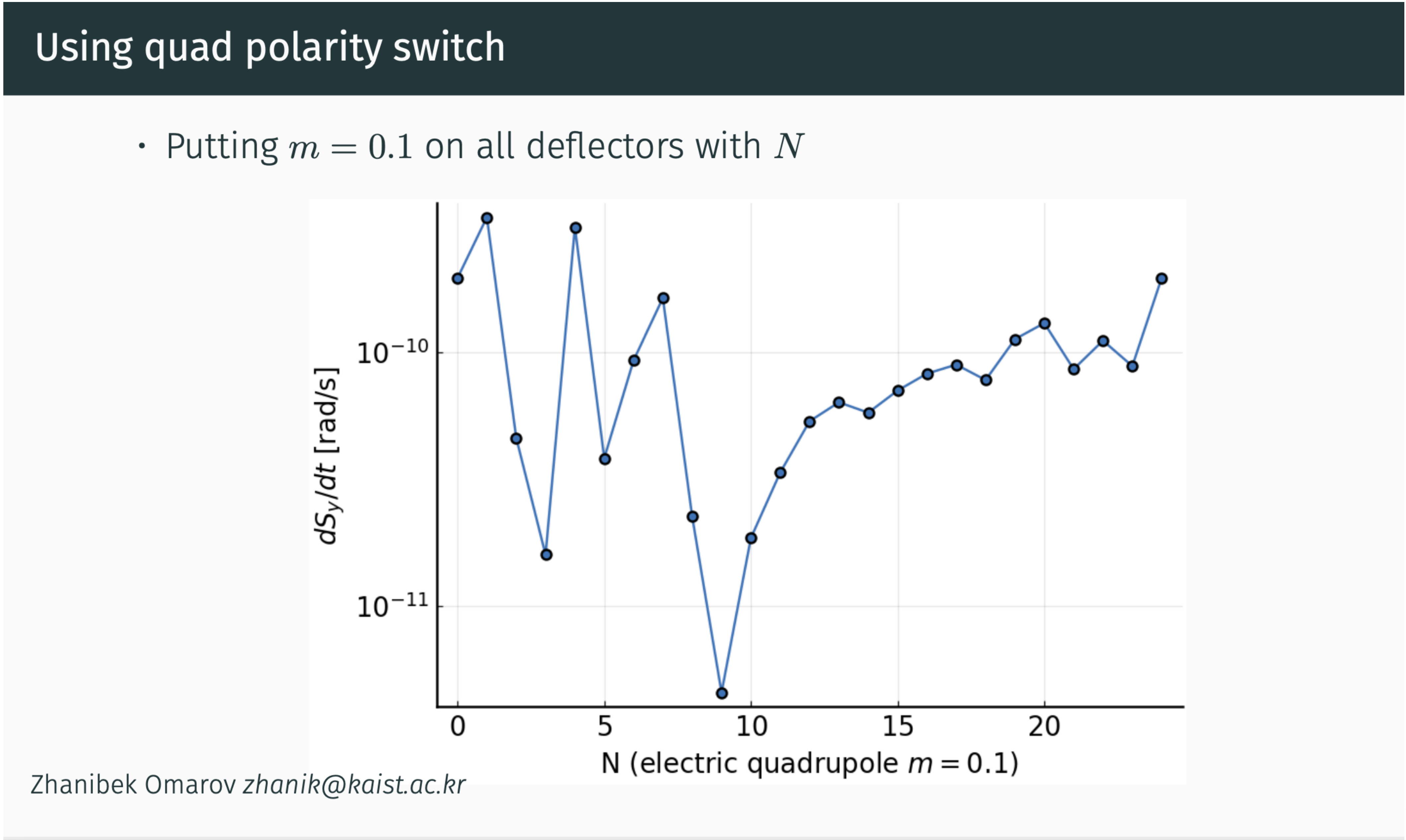
- Let's quantify the amount of electric quadrupole component in terms of m equivalent

Electric quad-field, *m*=0.1, on all deflectors with *N*, apply an average B_x = 1nT with random *N* distribution



N: Azimuthal harmonic of (unwanted) electric quad field

Electric quad-field effect with magnetic quad current flip



Using quad polarity switch

- Putting $m = 0.1$ on all deflectors with N

Zhanibek Omarov *zhanik@kaist.ac.kr*

Electric quad-field from a displaced sextupole

m value for electric sextupoles

$$E_y = -2k^e xy$$

$$E_x = k^e(x^2 - y^2).$$

- Assume 100 um misalignment

$$E_y = 2 \times 200\,\mathrm{kV/m^3} \times 100\,\mathrm{um} \times y$$

$$E_y = \left(\frac{E_0(n-1)}{R_0}\right)y = \left(\frac{E_0 m}{R_0}\right)y$$

- Expected electric focusing: $m_6 = 2 \times 10^{-5}$
- Should be less with randomness

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